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## Life cycle analysis of forest carbon in the central appalachian region

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**LIFE CYCLE ANALYSIS OF FOREST CARBON IN THE CENTRAL APPALACHIAN  
REGION**

**Pradip Saud**

**Thesis Submitted to the Davis College of Agriculture, Natural Resources and Design  
at West Virginia University  
in partial fulfillment of the requirements  
for the degree of**

**Master of Science  
in  
Forestry**

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Morgantown, WV**

**2011**

**Keywords: carbon emissions; carbon balance; carbon credit; fossil fuel; energy  
consumption; harvesting system; hardwood processing.**

## ABSTRACT

### LIFE CYCLE ANALYSIS OF FOREST CARBON IN THE CENTRAL APPALACHIAN REGION

Pradip Saud

Forest management and wood product processing activities such as harvesting, transportation, and lumber processing consume fossil fuels and emit carbon dioxide. This emitted carbon dioxide creates credit carbon balance which is usually overlooked while estimating the carbon benefits from woody biomass and wood products. Accountability of carbon stored in woody biomass and wood products varies when such carbon emissions are considered. Factors such as, harvesting intensity, growth rate, dead trees and forest fires all affected the estimation of forest carbon balance while harvesting system determines the carbon emission from fossil fuel consumptions. Energy sources used in sawmills for electricity are also crucial in credit carbon balance analysis. Therefore, this study assessed (1) forest carbon balance of the mixed Appalachian hardwood forests and carbon emissions due to the use of fossil fuels in harvesting systems in West Virginia, and (2) carbon balance in hardwood lumber processing in the central Appalachian region. Data were obtained from a regional sawmill survey, public database and relevant publications.

Forest carbon balance and carbon emission were analyzed within a life cycle inventory framework of cradle to gate using sensitivity analysis and stochastic simulation. The results showed that the annual carbon balance of the forests per hectare was not significantly affected by carbon loss from the volume of removal, fire and dead trees. It was also found that carbon emission from combustion of fossil fuel using manual harvesting system was less than using mechanized harvesting systems. Though a minimal amount of carbon was emitted from harvesting systems, the forest carbon displacement rate during timber processing was affected largely by hauling compared to felling, processing, skidding and loading. Carbon emission quantity from fuel consumption and forest carbon displacement rate were also affected by harvest intensity, hauling, payload size, forest type, and machine productivity.

Credit carbon balance generated from lumber processing was statistically analyzed within the gate to gate life cycle inventory framework. Stochastic simulation of carbon emission and its impact on carbon balance and carbon flux during lumber processing were carried out under different operational scenarios. Credit carbon balance from electricity consumption varied among sawmills of different production levels and operation hours per week and also attributed effect of different head saws, lighting types and air compressors used at sawmills. Credit carbon balance significantly reduced the carbon accountability of the lumber in useful life period at first order of decay of carbon. Substantial amount of carbon flux attributed from energy consumption and exports of lumber reduced the carbon storage accountability of the lumber product. Increase of the carbon accountability of the lumber products and decrease of the carbon flux ratio could be achieved through using an efficient equipments at sawmills and an appropriate mixture of energy sources for electricity supply.

## **DEDICATION**

I wish to dedicate this thesis to *Kuladevata Ghatal*, father Pushkar Saud and mother Narmada Devi Saud who always inspire me to set goals. I am extremely indebted to my brother Tek Badhadur Saud, sister Himalaya Saud and sister in-law Pushpa Saud for their love and care through my study. Finally, I would like thank my friends Benktesh Das Sharma, Sabina Dhungana, Ishwar Dhami and Sudhiksha Joshi, who helped in several ways during my studies and stay at WVU.

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## **1. Introduction**

Forests are the largest terrestrial carbon (C) reservoir and sequester substantial amounts of carbon dioxide (Dixon et al., 1994). Carbon sequestration is regulated by tree growth, plant death and plant oxidation (Harmon et al., 1994; Huston and Gregg, 2003) and also on the initial size of stand stock or time period over which carbon sequestration is allowed (Schlamadinger and Marland, 1996). Depending upon species, carbon content may differ but research commonly posits that 50% of a plant's dry biomass is carbon (Smith et al., 2003). Several studies have focused on assessing the use of forest biomass sinks to sequester carbon as part of a global climate mitigation effort (Sedjo and Toman, 2001) and even using avoided deforestation principles to meet the target of carbon emissions credit (Sedjo and Sohngen, 2007).

The forest carbon cycle is composed of biological and industrial sub-cycles. Biological cycle indicates the annual sequestration or emission of carbon, whereas industrial cycle presents the carbon emissions and offset throughout the wood product life span. Both carbon cycles should be studied in concert (Gower, 2003) and the role of wood product carbon cycle is equally as important as the biological cycle for studying climate change (White et al., 2005). The net balance of forest carbon stock is influenced by transfer of carbon to the round wood or release of carbon into the atmosphere (Apps et al., 1999).

Carbon stored in trees serves as one carbon pool and the manufactured wood product serves as another pool. Depending on wood products use and end of life process, it creates a lag time and determines the rate of carbon return to the atmosphere (Karjalainen, 2002). When woody biomass is used as fuel to reduce fossil fuel combustion, it serves as the third pool (Oneil and Lippke, 2010). When wood products are used as the substitute of steel and concrete, the

displacing emission from these products serves as permanent emission offset and is called the substitution pool (Perez-Garcia et al., 2005).

Information on carbon stocks of wood products is useful in evaluating their potentials in GHGs mitigation (Brown et al., 1998; IPCC, 2003). Carbon emission estimation of wood products during their life time is affected by the decay rate and waste treatment practices. Decay rate influenced the estimate of the carbon pool and uncertainty of outflow (Winjum et al., 1998). One way of minimizing the uncertainty of the carbon pool estimates is to perform direct stock inventories of wood products (Pingoud et al., 2001). If practical stock inventories are available, we can directly estimate carbon stock changes and verify parameters during the modeling process (Pingoud et al., 1996). Such estimates need to consider the life cycle analysis of wood products. Therefore, most estimates of carbon stocks and stock changes are based on indirect calculation models using hypothetical parameters (Apps et al., 1999; Harmon et al., 1994; Kurz et al., 1992).

Previous forest carbon assessments have focused only on changes in biomass carbon and assumed that GHGs emissions from forestry activities are minimal. This assumption not only omits a potentially significant source of emissions from forest management but also precludes the evaluation of differences in emissions from alternative forest management intensity choices by forest landowners (Sonne, 2006). Such greenhouse gas emission occurring from changes of carbon stock in forests and products could be complex over time but it might be limited when sustainable forest management is practiced over a long time (Gustavsson et al., 2006).

Carbon stored in trees is removed through harvesting process. Carbon stored in harvested timber also varies among tree species (Smith et al., 2003). Carbon emission occurred from the use of energy or fossil fuel sources in harvesting and wood product processing is usually

overlooked while accounting carbon sequestration through forest and wood products. The carbon dioxide generated through such energy and fossil fuel sources is a contributing factor affecting for both global warming and greenhouse gases (GHG) (Wilson and Dancer, 2005). Identifying the major sources of carbon dioxide emission and quantifying its magnitude from forest management and wood product processing are critical in developing policies to reduce carbon emissions (White et al., 2005). Concurrently increasing environmental regulations, government policies and public concerns have challenged forest management and wood product processing. It sought the importance of Life Cycle Inventory (LCI) of the forest management and forest product manufacturing activities (USEPA, 2009; Puettmann et al., 2010). The importance of carbon storage in woody biomass relays when there is a clear depiction and quantification of the carbon emissions from energy involved in timber harvesting and wood products manufacturing. Therefore, the pre- and post-forest management activities are essential to evaluate carbon emissions form energy consumptions during timber harvesting and wood product manufacturing, and the net carbon offset in the forest carbon cycle.

Though several guidelines can be used to conduct Life Cycle Analysis (LCA) to identify where, when, and how environmental impacts occur throughout a product's life, the most widely accepted methods are set forth in the International Standard Organization (ISO) 14000 series of standards (ISO, 2006). Most recently, the Intergovernmental Panel on Climate Change (IPCC, 2006) and the US Environmental Protection Agency (USEPA, 2010) have also developed guidelines for calculating greenhouse gas emission and sink, specifically for the carbon emission from the use of energy sources in forest management and wood product processing. Due to the concerns raised on negative carbon emissions, the Consortium for Research on Renewable Industrial Materials (CORRIM) has changed the protocol to access LCA for forest management

and wood products. It shows that the carbon stored in products is functionally equivalent to negative carbon emissions generated from the manufacture of wood products (Puettmann et al., 2010; Lippke et al., 2010).

LCI helps to quantify energy and raw material requirements, air emissions, waterborne effluents, solid wastes and other environmental releases occurred within the system boundary. Fuel and electricity are the two most important energy elements used in forest harvesting and wood product manufacturing (Wilson and Dancer, 2005; Oneil et al., 2010; Puettmann et al., 2010). LCI has been increasingly used in policy decision making for greenhouse gas reduction in the forest sector but the related database has been limited at the unit-process level of wood products due to practical difficulty in gathering data.

The Appalachian region sequesters significant amount of atmospheric carbon through vast area of mixed hardwood forests. A significant amount of timber is harvested and processed annually that change the forest carbon and wood carbon inventory. However, fossil fuels and other energy sources used in harvesting and wood processing are typically not considered as issues for atmospheric carbon flux and factors affecting accountability of carbon stored in forest and wood products. This necessitates the analysis of forest carbon balance in the central Appalachian region within a life cycle inventory framework incorporating forest status, harvesting system, sawmill size, processing equipment, and energy usage. Therefore, the objectives of this study were to conduct a life cycle analysis on: (1) forest carbon balance and carbon emissions of timber harvesting in West Virginia, and (2) carbon balance of hardwood lumber processing in the central Appalachia region.

## References

- Apps, M.J., Kurz, W. A., Beukema, S. J. and Bhatti, J, S, 1999. Carbon budget of the Canadian forest product sector. *Env. Sci. Policy* **2**, 25–41.
- Brown, S., B, Lim. and B, Schlamadinger. 1998. Evaluating approaches for estimating net emissions of carbon dioxide from forest harvesting and wood products. Meeting Report, IPCC/OECD/IEA Program on National Greenhouse Gas Inventories, Dakar, Senegal, 5-7 May 1998. pp. 20.
- Dixon, R. K., S, Brown., R. A., Houghton, A. M., Solomon, M. C. Trexler, and J. Wisniewski. 1994. Carbon pools and flux of global forest ecosystems. *Science*. 263:185-190.
- Gower, S. T. 2003. Patterns and mechanisms of the forest carbon cycle. *Annu. Rev. Env. Resour.* 28: 169–204.
- Gustavsson, L., Madlener, R., Hoen, H. F., Jungmeier, G., Karjalainen, T., Klohn, S., Mahapatra, K., Pohjola, J., Solberg, B., Spelter, H.2006. The role of wood material for greenhouse gas mitigation. *Mitigation and adaptation strategies for global change, 2006-11*, 1097- 1127.
- Harmon, M. E., Harmon, J. E., Ferrell, W. K., and Brooks, D. 1994. ‘Modeling carbon stores in Oregon and Washington forest products: 1900–1992’, *Climatic Change* **33**, 521–550
- Huston, M. A. and Gregg, M. 2003. Carbon management and biodiversity. *Journal of Environment Management* 67(2003) 77-86.
- IPCC, 2003. Intergovernmental Panel on Climate Change Estimation, Reporting and accounting of harvested wood products – Technical Paper. UNFCCC paper, pp 44.

- IPCC, 2006. Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan. Vol. 4 AFOLU, Chapter 4, pp. 83.
- ISO, 2006. Environment management – Life cycle assessment- Requirements and guidelines. International Organization for Standardization (ISO 14044:2005[E]) 54 pp
- Karjalainen, T., Pussinen, A., Liski, J., Nabuurs, G.J., Erhard, M., Eggers, T., Sonntag, M., Mohren, F. 2002. An approach towards an estimate of the impact of forest management and climate change on the European forest sector budget: Germany as a case study. *Forest Ecology and Management* 162:87-103
- Kurz, W. A., Apps, M. J., Webb, T. M. and McNamee, P. J. 1992. The carbon budget of the Canadian forest sector: Phase I, Information Report NOR-X-326, Forestry Canada, Northwest Region, Forestry Centre, 93 pp.
- Lippke, B., Wilson, B., Meil, J., and Taylor, A. 2010. Characterizing the importance of carbon stored in wood products. *Wood and fiber science*, March 2010 V. 42(CORRIM special issue), pp 5-14.
- Oneil, E. E., and Lippke, B. R. 2010. Integrating products, emissions offsets and wildlife into carbon assessments of Inland Northwest forests. *Wood and fiber science*, March 2010 V. 42(CORRIM special issue). pp 145-163.
- Pingoud, K., Perälä, A.-L., and A. Pussinen. 2001. Carbon dynamics in wood products. *Mitigation and Adaptation Strategies for Global Change* 6: 91–111, 2001. 42, Kluwer Academic Publishers, Netherland. 2001
- Pingoud, K., Savolainen, I., and Seppälä, H. 1996. Greenhouse impact of the Finnish forest sector including forest products and waste management. *Ambio* 25, 318-326.

- Perez-Garcia, J., Lippke, B., Briggs, D., Wilson, J., Bowyer, J., & Meil, J. 2005. The environmental performance of renewable building materials in the context of residential construction. *Wood and Fiber Science*. 37, 3–17
- Puettmann, M. E., Bergman, R., Hubbard, S., Johnson, L., Lippke, B., Oneil, E., Wanger, F. G., 2010 Cradle to gate life cycle inventory of US products production: CORRIM phase I and phase II products. *Wood and fiber science*, March 2010 V. 42(CORRIM special issue), pp 16-28.
- Schlamadinger, B., & Marland, G. 1996. The role of forest and bioenergy strategies in the global carbon cycle. *Biomass Bioenergy* 10, 275–300.
- Sedjo, R. A and Sohngen, B. 2007. Carbon credits for avoided deforestation. Discussion Paper October 2007, RFF DP 07-47, pp 01-08.
- Sedjo, R.A. and Toman, M. 2001. Can carbon sinks be operational? RFF Workshop Proceedings, Resources for the Future, Discussion Paper 01–26.
- Smith, J.E., L.S. Heath, and J.C. Jenkins. 2003. Forest volume-to-biomass models and estimates of mass for live and standing dead trees of U.S. forests. United States Department of Agriculture, Forest Service, General Technical Report NE-298, Newtown Square, Pennsylvania. 57-p
- Sonne, E. 2006. Greenhouse gas emissions from forestry operations: A life cycle assessment. *Journal of Environmental Quality* 35:1439–1450
- USEPA, 2009, Environmental Protection Agency (EPA). 40 CFR Parts 86, 87, 89 et al. Mandatory reporting of greenhouse gases; Final Rule, Federal Register / Vol. 74, No. 209 / Friday, October 30, 2009 / Rules and Regulations, pp 56260-56519.



- USEPA, 2010. Environmental Protection Agency (EPA). Inventory of US greenhouse gas emissions and sinks: 1990-2008, April 15, 2010, pp 407.
- White, K. M., Gower, S.T., and Ahl, D. E. 2005, Life cycle inventories of round wood production in northern Wisconsin: Inputs into an industrial forest carbon budget. *Forest Ecol. Management* 219, 13-38
- Wilson, J.B. and Dancer, E. R. 2005. Gate to gate life cycle inventory of laminated veneer lumber production. *Wood and Fiber Science*, 37 CORRIM Special Issue, 2005, pp 144-127.
- Winjum, J. K., Brown, S and Schlamadinger, B. 1998. Forest harvests and wood products: sources and sinks of atmospheric carbon dioxide. *Forest Science* 44:272-284.

**2. A LIFE CYCLE ANALYSIS OF FOREST CARBON BALANCE AND CO<sub>2</sub> EMISSIONS OF TIMBER HARVESTING IN WEST VIRGINIA<sup>1</sup>**

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<sup>1</sup> To be submitted to Wood and Fiber Science

## **Abstract**

Forest management activities such as harvesting and transportation emit carbon dioxide (CO<sub>2</sub>) and this emission is usually overlooked when estimating the carbon benefits from woody biomass. This study assessed the net aboveground biological carbon balance of the central Appalachian mixed hardwood forests in West Virginia and carbon emissions from the use of fossil fuels in harvesting systems including felling, processing, skidding, loading, and hauling of timber to a sawmill or a processing facility. A life cycle inventory framework of ‘cradle to gate’ was used to analyze the forest carbon balance and emission using sensitivity analysis and stochastic simulation of Monte Carlo. The results showed that the annual carbon balance of the forests per hectare was not significantly affected by carbon loss from the volume of removal, fire and dead trees. It was found that an average carbon emission was  $5.06 \pm 0.90$  metric tons per thousand cubic meters (tC/TCM) using manual harvesting system, or  $6.84 \pm 1.22$  tC/TCM using mechanized harvesting system. Both harvesting systems had an average of 80 km hauling distance. Though minimal amount of carbon was emitted from fossil fuel used in mechanized operations, the forest carbon displacement rate during timber processing were affected largely by hauling process compared to felling, processing, skidding and loading. Species group, forest type, and harvest intensity were attributed to the variation of forest carbon displacement rate and carbon balance of harvested timber. Uncertainty of carbon emission amounts from fuel consumption and forest carbon displacement rate were also coupled to hauling distance, payload size, forest type, and machine productivity.

## 2.1 Introduction

Increasing concentration of carbon dioxide (CO<sub>2</sub>) and other greenhouse gases (GHGs) in the atmosphere instigate to develop the strategies to mitigate climate change impact (Petit et al., 1999; Vannien and Makela, 2004; IPCC, 2006). One of the climate mitigation policies is to focus on increasing the amount of carbon stored in forests and forest products and quantifying the carbon (C) budgets of forest stands (Raupach et al., 2007; Hennigar et al., 2008). Forests, being the largest terrestrial carbon reservoir (Dixon et al., 1994), are adapted to increase the forest carbon stock using different management strategies and practices (Richard et al., 1997). The fate of forest carbon is determined by the use and end use of wood products (Perez-Garcia et al., 2005; Puettmann et al., 2010; Sharma et al., 2011).

The forest carbon cycle can be distinguished into biological and industrial cycles. The forest biological cycle represents the sum of all carbon flux including an annual sequestration or emission in forests while the industrial cycle indicates the net emission of carbon throughout forest product life span (Gower, 2003; White et al., 2005). The net carbon flux from forest to industry is close to zero when forest is being managed for timber production under sustainable principles. Carbon stock in forests managed under sustainable forestry principles can help to increase net carbon sequestration (Straka and Layton, 2010; Sharma, 2010). Carbon emissions remain neutral or negative over time in sustainably managed forests where harvest contributes to the sustainable product pools and post-product life pools, increasing sustainability (Lippke et al., 2010).

Forests managed under sustainable principles have a biological foundation with inputs and outputs that can be incorporated into life cycle analysis (LCA) (Straka and Layton, 2010). LCA ensures that forest sustainability standards are being met and measures environmental

impacts of management activities. Therefore, LCA can help to understand and characterize the opportunity of reducing carbon emissions into the atmosphere, and evaluate whether our activities are motivated towards carbon storing or carbon generating (Oneil et al., 2010). Defining forest carbon in a “closed” system not only helps conclude carbon sequestration from tree growth but also accounts carbon loss from dead trees as it decomposes (Harmon, 2001). The coarse woody biomass of dead trees also changes the carbon storage of the ecosystem significantly (Janisch and Harmon, 2002). Likely, forest carbon and emission models that include carbon loss from forest fire helps develop strategies to reduce the threat of catastrophic wildfire (Bonnicksen, 2008).

Many previous studies have simulated hypothetical forest modeling processes to demonstrate different management scenarios and harvesting schedules reflecting minimal difference in carbon storage (Schlamadinger and Marland, 1995; Perez-Garcia et al., 2005; Hennigar et al., 2008). These studies optimize the forest carbon stock with intensive forest management that can offset carbon emissions from raw material extraction and transportation while the carbon emissions from machinery are undetermined. In the human assisted biological carbon cycle, carbon is sequestered and then emitted. It occurs due to combustion of fossil fuels, such as diesel, gasoline, and lubricants used in equipment used for seedling production, plantation, fertilization, harvesting, and transportation of final products to a sawmill (Oneil et al., 2010; Puettman et al., 2010).

Forest harvesting intensity affects carbon emissions of machines and it also depends on factors such as supply, demand, and ownership. It is found that carbon emitted to the atmosphere and carbon sequestered differed by 12% among three different ownership types, i.e. national forest, state forest and non-industrial private forest (White et al., 2005). Employed harvesting

systems could be either manual or mechanized and its preference determines harvesting productivity and cost (Li et al., 2006; Oneil et al., 2010). The fuel consumption rates of each manual or mechanized harvesting process differs (Wang et al., 2004a, 2004b; Oneil et al., 2010). Likely, fuel consumption rates vary among truck types for hauling harvested timber to sawmill.

An assessment of forest carbon that includes timber harvesting intensity level, forest growth rates, dead trees and forest fire loss could be beneficial to account net forest carbon balance of the existing forest stock. Similarly, consideration of the different forest group types, harvesting systems, harvesting residue extraction systems, and truck types, would be useful to illustrate the variation of carbon emission rates that occurred from different fossil fuel consumption in the process. Thus, it is an imperative to analyze and quantify the forest carbon balance and variation in carbon emission that occurred from fossil fuel in the process of evaluating existing management and harvesting practices in order to consider whether sustainable forest management practices exist or not. Therefore, this study aims to evaluate the net carbon offset of central Appalachian hardwood forests under current management and harvesting strategies using life cycle inventory (LCI) approach. The specific objectives were to (1) assess the forest carbon balance of mixed hardwood forests in West Virginia, and (2) analyze the carbon emissions from fuel combustions of harvesting systems in West Virginia.

## **2.2 Materials and Methods**

### **2.2.1 Data**

Naturally regenerated forests in West Virginia that represent the central Appalachian region sequester a vast quantity of atmospheric carbon and offset carbon emissions from fossil fuel consumption in machinery and industrial purposes. Forestland covers almost 76% of the state (USDA FS, 2010) and 71% of the forests are privately owned (Milauskas and Wang, 2006; USDA FS, 2010). Data obtained from published literature and public databases were normalized and coordinated, within a cradle to gate (sawmill gate) life cycle inventory framework, according to inventory data collection rules (ISO, 2006) and good practice guidance for forestry practices (IPCC, 2006a; 2006b). The system boundary was setup for harvesting systems that include fuel consumption in terms of felling, processing (topping and delimiting), skidding, loading, and hauling (Fig 2.1). We selected a thousand cubic meter (TCM) volume of the harvested hardwood logs as the base functional unit in the harvesting system.

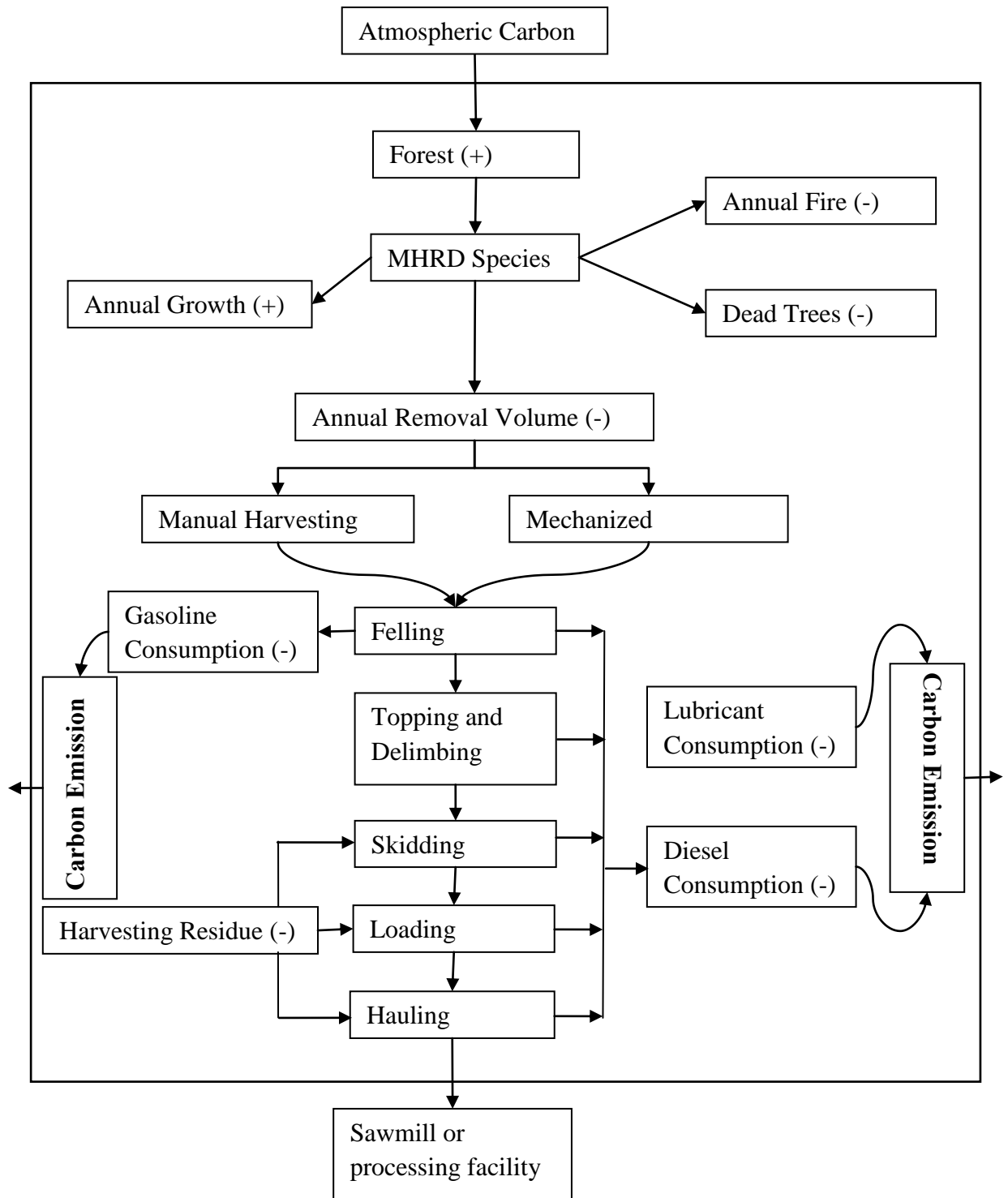
Timberland data were obtained from an online Forest Inventory Database (FIDO) by USDA Forest Service (USDA FS, 2010). Annual growing stock, annual removal, annual mortality (dead and fire), and annual growth of the forest tree species group were categorized by species groups. Net volume of live trees above 12.7cm (>5 inches) diameter at breast height (dbh) was included in carbon analysis since these trees were assumed to be commercially useful for either pulp and paper or structural purpose. Inventory data on net volume of live trees and net volume of dead trees were available for 2000, 2004, 2005, 2006, 2007, 2008 and 2009. However, data on net growth volume and harvested volume were only available for the years 2000, 2006, 2008 and 2009.

Harvested residue biomass ( $BHres_i$ ) by species group ( $i$ ) was estimated as green weight in metric tons using Eq 2.1. The product of harvested volume ( $Hv_i$ ) is in  $m^3$  and density is in green weight ( $Dengwt_i$ ) in  $tons/m^3$ . It was assumed that 29% of total stem biomass is contained in branches and tops for every ton of biomass contained in tree stem in the Northeastern region (INRS, 2007). It was also assumed that only 65% of wood residue can be economically extracted and available due to technical and topographic feasibility (Perlack et al., 2005). Since forest fire is another important factor for forest carbon loss, we estimated carbon emissions due to fires from 2002 to 2009 based on the data obtained from West Virginia Division of Forestry (<http://www.wvforestry.com/dailyfire.cfm>) (WVDOF, 2010).

Statistical analysis was conducted using R 2.9.2 statistical package and significance testing was carried out at the 95% confidence level. One sample t-test was used to test significant difference of annual mean carbon stock (forest stock), mean carbon growth (forest growth) and mean carbon removal (forest harvest) of the forest. Similarly, the significant difference in mean carbon emissions among harvesting systems and among fuel consumption rates was tested. We also conducted Two Sample, two sided t-test assuming the true variance for the ratios of variance less than the critical F-value.

$$BHres_i = 65\% * (Hv_i * Dengwt_i * 29) / 71 \quad \forall i. \quad (2.1)$$





**Figure 2.1 Life cycle inventory framework and system boundary.**

*Minus sign (-) denotes decrease in carbon balance/stock and plus sign (+) denotes increase in carbon balance/stock.*

## 2.2.2 Forest Carbon Estimation

Carbon content ( $CH_{v_i}$ ) of tree species ( $i$ ) in harvested volume ( $H_v$ ) was estimated in metric tons using Eq. (2.2). The harvested volume ( $H_{v_i}$ ) was multiplied by specific gravity ( $Sg_i$ ) of the tree species at oven dry weight (Alden, 1995) for each tree species and assumed carbon is 50% of weight (Smith et al., 2006). Carbon content in wood residue ( $CB_{Hres_i}$ ) was also estimated at oven dry weight in metric tons (Eq. 2.3). Carbon content by forest type of harvested timber and wood residue were derived by allocating an average harvest percentage of each species for the total harvested volume of that forest type group. Carbon sequestered by dead trees ( $CB_D$ ) was also estimated in metric tons. Carbon loss from forest fires ( $CB_F$ ) was estimated in metric tons using the product of an average estimated carbon content of the current forest productivity per unit area in hectare ( $ha$ ) and burnt forest area.

Net carbon balance ( $CB_L$ ), in metric tons per hectare (tC/ha), of the aboveground stem biomass was estimated (Eq. 2.4) by subtracting mean carbon removal through  $CH_V$ ,  $CB_D$ , and  $CB_F$  from existing carbon stock ( $CS$ ) and multiplying by the mean carbon growth ( $CB_G$ ). It was also simulated for 200 years using mean carbon loss and standard deviation through Monte Carlo simulations to examine the uncertainty of forest carbon balance using mean ( $\mu$ ) and standard deviation ( $\sigma$ ) assuming a normal distribution of the randomly generated 1000 numbers. Forest carbon displacement rate ( $DC_r$ ) that determines reduction in carbon balance of harvested timber at the expense of carbon emission from fossil fuel consumption was calculated using Eq. (2.5). However, this study does not take into account the carbon sequestered by roots, branches, foliage and leaf litter on the forest floor.

$$CH_{v_i} = 0.5 * H_{v_i} * Sg_i \quad \forall i. \quad (2.2)$$

$$CBHres_i = \frac{BHres_i}{Dengwt_i} * Sg_i * 0.5 \quad (2.3)$$

$$C_{BL} = CB_G * (CS - CH_V - CB_D - CB_F) \quad (2.4)$$

$$DC_r = \frac{CH_{Vi} - TCF_c}{CH_{Vi}} * 100\% \quad (2.5)$$

### 2.2.3 Forest Harvesting and Fuel Consumption

We only considered the clear-cut (CC) scenario because of limited data on other forest harvesting methods. Manual and mechanized harvesting systems are the two most commonly used systems in the central Appalachian region (Milauskas and Wang, 2006). A manual harvesting system includes tree felling with chainsaw, and a cable skidder for skidding while mechanized harvesting system consists of tree felling with feller buncher, and skidding with a grapple skidder. Other processing functions are assumed to be the same for these two harvesting systems, including delimiting and topping with chainsaws, loading with large loader, and log truck for hauling timber.

Data on machine utilization, fuel consumption, and productivity for manual harvesting were based on a study by Wang et al. (2004a) (Tables 1 and 4). Manual harvesting was performed on sites with slopes from 10 – 45%, tree diameters of 20.3 to 66 centimeters, and tree merchantable heights of 2.43 -17 meters. Similarly, mechanized harvesting analysis was based on previous studies (Wang et al., 2004b; Oneil et al., 2010) (Tables 2, 3 and 5). These harvested sites represent typical central Appalachian harvesting with slope from 0 – 30% (Wang et al., 2004b). Site conditions representing the Northeast and North Central regions were based on a study by Oneil et al. (2010).

We normalized the machine's productivity with delay time (Table 1). Fuel consumption rates were estimated for selected harvesting machines (Brinker et al. 2000). An average tree distance was assumed to be approximately 3.048 meters (10 feet) depending on stand density (USDA FS, 2010). An average extraction distance of 500 meters (equivalent to 1640.41 feet) was assumed with an average payload size of 3.114 m<sup>3</sup> (equivalent to 110 ft<sup>3</sup> or 3-5 long logs) for skidders (Wang et al., 2004a; 2004b).

Gasoline and oil (lubricant) consumption was estimated for chainsaws. Chain saw; Husqvarna 55 consumes 10 ml/min at 8500 rpm (operator manual, Husqvarna 2002) and Husqvarna 372 consumes 4-20ml/min (Husqvarna, 2002). Therefore, an average consumption of 0.6 lit/hr and 0.72 lit/hr of gasoline, and 0.012 lit/hr and 0.014 lit/hr of lubricant was estimated for Husqvarna 55 and Husqvarna 372, respectively. Similarly, it was assumed that 4-axle log truck hauls 23 m<sup>3</sup> of timber as payload (an average equivalent to 20-21 metric tons depending on green weight of logs) for an average hauling distance of 80 km (equivalent to 50 miles) that includes 16 km of gravel (unpaved) road 64 km of paved road. It was assumed that it consumes 31.4 liters of diesel and 0.73 liter of lubricant for one way travel of 80 km distance but the fuel consumption rate of a loaded trucks travelling on a gravel roads was twice that than on paved roads (McCormark, 1990). The return distance of a hauling truck to forest was also included, but the fuel consumption of the returning truck on a gravel road was not doubled that on a paved road. The estimated pay load incorporates the restriction on the hauling capacity and gross vehicle weight for single unit tandem (4 axles) and tractor-semi trailer (5 axles) in West Virginia (Spong, 2007). For extracting logging residue, the machine productivity and fuel consumption rate for cable and grapple skidders were normalized to a skidding distance of 500 m (Li et al., 2006) (Table 2.1). The productivity rate and fuel consumption rate of the loader was assumed to

be the same for both harvesting systems. We also assumed the dump truck was used for residue hauling with a capacity of 25 tons. But we considered hauling 20 tons or less of unchipped residues, and used the same fuel consumption rate as long log truck (English et al., 2000).

**Table 2. 1 Machine productivity and fuel consumption rate.**

Process	Machine and Model	Hp	Productivity (m <sup>3</sup> /PMH)	Diesel L/m <sup>3</sup>	Lubrica nt L/m <sup>3</sup>
Mixed hardwood timber					
Felling with topping and delimiting	Chain Saw, Husqvarna 372 <sup>a</sup>	5.4	3.87 <sup>a</sup>	*0.19 <sup>e</sup>	0.004 <sup>e</sup>
Skidding	Cable skidder, Timber <sup>a</sup> Jack 460	174	7.69 <sup>a</sup>	1.72 <sup>a</sup>	0.49 <sup>b</sup>
Felling	Feller buncher, Timbco 445 C	260	25.25 <sup>b</sup>	2.08 <sup>d</sup>	0.22 <sup>c</sup>
Topping and delimiting	Chain Saw, Husqvarna 55 <sup>a</sup>	3.4	5.06 <sup>c</sup>	*0.16 <sup>e</sup>	0.003 <sup>e</sup>
Skidding	Grappler skidder Timber jack 460 <sup>a</sup>	172	7.21 <sup>c</sup>	1.84 <sup>c</sup>	0.52 <sup>c</sup>
Logging residue					
	Cable skidder	NA	5.66 <sup>e</sup>	1.34 <sup>e</sup>	0.80 <sup>e</sup>
	Grappler Skidder	NA	14.50 <sup>e</sup>	0.84 <sup>e</sup>	0.31 <sup>e</sup>
**Loading	Large Loader	NA	13.17 <sup>b</sup>	1.437 <sup>b</sup>	0.026 <sup>b</sup>
**Hauling	Long log truck	NA	7.77 <sup>b</sup>	12.73 <sup>b</sup>	0.229 <sup>b</sup>

\*Represent gasoline consumption instead diesel; \*\*Represent common process of harvesting; PMH = Productivity per Machine Hour; PMH calculation includes productive time and delay time delay time, <sup>a</sup> Wang et al 2004a; <sup>b</sup> Oneil et al 2010; <sup>c</sup> Wang et al 2004b; <sup>d</sup> Brinker et al 2000. <sup>e</sup> Hasqvarna 2002, 2011; Li et al 2006.

#### 2.2.4 Carbon Emissions from Fuel Consumptions

C emissions were calculated for both manual and mechanized harvesting systems. Carbon emissions from fossil fuels like diesel combustion ( $CD_C$ ) and gasoline combustion ( $CG_C$ ) were

based on the carbon dioxide emission estimates by USEPA (2005). C emission from lubricant consumption ( $CL_c$ ) was calculated using the method for industrial product and process by IPCC (2006). The default carbon content of lubricant, 20.0 kg C/GJ was used based on a lower heating value basis. Using the principles outlined in the Good Practice Guidance of IPCC (2006) and by USEPA (2010) total carbon emissions ( $TCF_c$ ) was estimated.  $TCF_c$  (Eq. 2.6) from fossil fuel consumption in timber harvesting, residue extraction, and timber and residue hauling process was based on the calculation of C emissions from diesel (Eq.2.7), lubricants (Eq. 2.8) and gasoline (Eq. 2.9).

$$TCF_c = CD_c + CL_c + CG_c \quad (2.6)$$

$$CD_c = \left\{ \sum_{k=1}^n Hv \left( \frac{\sigma_{mk}}{Pm_m} + \frac{\sigma_{ok}}{Pm_o} + \frac{\sigma_{pk}}{Pm_p} \right) + \frac{Hv}{pd} (d_g * 2\gamma_q + d_p * \gamma_q) \right\} \alpha * \delta \quad \forall k. \quad (2.7)$$

$$CL_c = \left\{ \sum_{k=1}^n Hv \left( \frac{\varphi_{mk}}{Pm_m} + \frac{\varphi_{nk}}{Pm_n} + \frac{\varphi_{ok}}{Pm_o} + \frac{\varphi_{pk}}{Pm_p} \right) + \frac{Hv}{pd} (d_g * 2\partial_l + d_p * \partial_l) \right\} \beta * \delta \quad \forall k. \quad (2.8)$$

$$CG_c = \frac{\tau_{nk}}{Pm_n} * \eta * \delta \quad \forall k. \quad (2.9)$$

Where,  $Hv$  is the harvested volume ( $m^3$ ) of timber,  $k$  is the  $k^{th}$  harvesting system (1 = manual, 2 mechanized);  $\sigma$ ,  $\varphi$ , and  $\tau$  are diesel, lubricant, gasoline consumption rate (liters per hour) of machine  $m$ ,  $n$ ,  $o$ , and  $p$  in harvesting system  $k$ ;  $Pm$  is the productive machine hour of the involved machine  $m$ ,  $n$ ,  $o$  .and  $p$ ;  $pd$  is the net payload (tons) of hauling truck;  $\gamma_q$  and  $\partial_q$  are diesel and lubricant consumption rates per km (liters/km) of hauling truck,  $d_g$  is the gravel

distance (km),  $dp$  is the paved distance in km,  $\alpha$  is CO<sub>2</sub> emission (tons) from diesel,  $\beta$  is CO<sub>2</sub> emission (tons) from lubricant,  $\eta$  carbon emission (tons) from gasoline and  $\mathcal{C}$  is molecular weight of carbon (tons).

### 2.2.5 Sensitivity Analysis

Sensitivity analysis of carbon emissions from timber harvesting was conducted in terms of skidding distance, hauling truck types, hauling distance, and payload size. In conjunction with hauling distance and payload size, forest type was also used to analyze the forest carbon displacement rate. Skidding distance ranged from 300 to 1000 m for both cable skidder and grapple skidders. Similarly, hauling distance was categorized as 80, 160, 240 and 300 km (50, 100, 150 and 200 miles) and 80 km hauling distance as a base case (Harouff, 2008). Based on the payload capacity and fuel consumption rate, five hauling truck types were considered with a maximum payload capacity of 14, 19, 23, 28, 30 m<sup>3</sup> for single axle, single unit tandem with 3 axle, single unit tandem with 4 axles, tractor-semi trailer with 5 axles and six-axle long loggers, respectively (Mason et al., 2008; Spong, 2007; Timson, 1974). For six-axle long logger, diesel consumption rate was assumed to be 8.04 km/lit (5 miles/gallon) and lubricant was assumed to be 708.5 km/lit (6 gallon oil change at 10000 miles) with an average payload of 26.7 metric tons (Mason et al., 2008). Hence, we assumed, 9.65, 11.26, 12.87, 14.48 km/lit (6, 7, 8, 9 miles/gallon) of diesel consumption for these five types of trucks as the payload size decreases. Similarly, we also assumed lubricant consumption rate of 850 km/liter (5 gallon oil change at 10000 miles drive) for single axle truck and single unit tandem with 3 axles, but for others hauling truck types lubricant consumption rate was assumed to be same as six-axle truck.

Forest carbon displacement rate from hauling distances (80, 160, 240 and 320 km) was also analyzed by forest group types for harvesting system and harvested residue extraction system assuming mixed hardwood species as a base case. We categorized tree species into three major forest type groups based on national core field guide for North Central and Northeast regions (USDA FS, 2006). The selected major forest groups were (1) Oak-hickory which includes all oak species, hickory, black walnut and yellow-poplar, (2) Ash-cottonwood, and (3) Maple, beech, basswood and birch. Four different scenarios of carbon emissions for mechanized and manual harvesting systems of mixed hardwood species were simulated to examine the uncertainty of carbon emissions using Markov-chain Monte Carlo (MCMC pack) simulation in R. For both harvesting systems, carbon emissions from harvesting and hauling up to 80 km distance was assumed as a base case scenario while 160, 240 and 320 km distances included as there different scenarios. Annual carbon emissions amount from harvesting systems was proportioned to per unit of the periodic mean harvested timber volume. The obtained value was simulated for 1000 times with a known variance (normal likelihood) and assuming a conjugate normal prior mean for hauling distance of 160, 240, 360 km using two different harvesting systems.

## **2.3 Results and Discussion**

### **2.3.1 Forest Carbon Balance**

In West Virginia, annual net volume of mixed hardwood forest is  $689 \pm 30.16$  million cubic meters with mean carbon stock of  $46.76 \pm 2.06$  tC/ha. Annual average carbon stock (tC/ha) of forestlands was significantly different over the years ( $p = 1.430e-09$ ) due to different growth in volume. The annual growth in volume of live trees increased annual carbon growth (increase



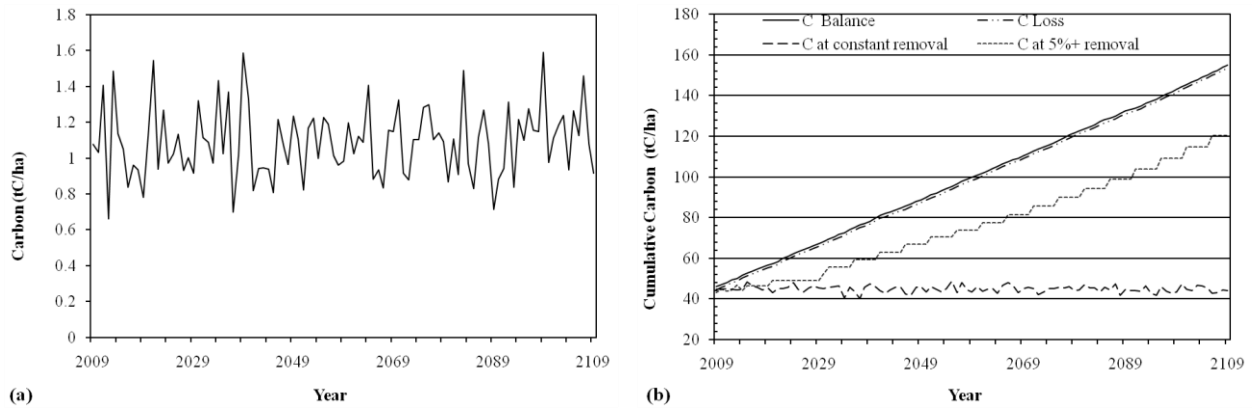
in forest carbon stock) and it was also significantly different over the years ( $p = 0.001386$ ). This annual tree growth added  $1.09 \pm 0.19$  tC/ha to the existing carbon stock. It was found that the simulated annual carbon growth would range from 0.63 to 1.69 tC/ha for the next 100 years (Fig 2.2a). Annually,  $2.6 \pm 0.44$  million tons of carbon (Mt C) stored in trees were removed through harvesting from timberland with an average removal of  $44.89 \pm 1.69$  tC/ha. The mean carbon stock (tC/ha) and carbon removed (tC/ha) were significantly different among tree species groups. For example, yellow-poplar shares an average of 11% of the timberland stock but it was harvested with an average of 20% of the annual timber harvested volume.

Annually, forest fires also depletes  $0.21 \pm 0.03$  Mt C stored in timberland and it attributed to carbon loss of an average of  $0.05 \pm 0.02$  tC/ha. Since smaller amount of forest carbon loss occurred due to forest fire, it would not significantly reduce net forest carbon balance (tC/ ha). An annual carbon loss from net dead trees is  $28.63 \pm 15.06$  Mt C with an average of  $6.35 \pm 3.09$  tC/ha in West Virginia. Though large amount of carbon loss occurred from dead trees, carbon release time in atmosphere would be lagged by the time period required for wood decay. Normally 20 years period is required to release carbon from dead trees (Janisch and Harmon, 2002).

Existing carbon balance would be increased in coming years, but carbon loss from harvesting and forest fire would also increase simultaneously (Fig 2.2b). The pattern of carbon loss and carbon balance per hectare would be parallel to each other because annual forest growth per hectare was attributed to the volume of harvested timber and volume loss due to forest fire. Continuation of timber harvesting at the current mean annual harvest rate would be helpful to increase carbon balance (tC/ha) significantly with slight variation in annual carbon loss (tC/ha) due to dead trees (Figure 2b). However, this would not be possible in practice because of the

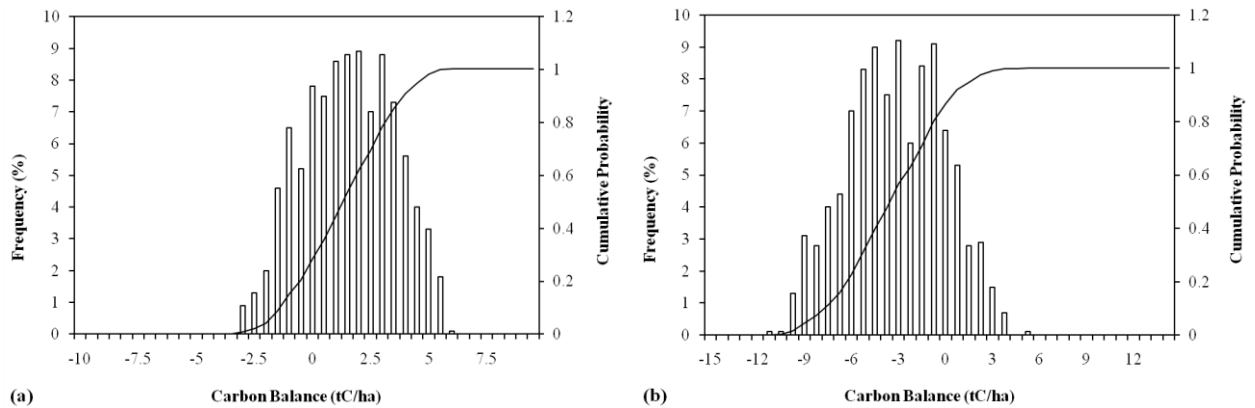
increasing demand of wood and wood products. Thus, if we increased current harvesting intensity (volume) by 5% and kept constant for consecutive five years and repeated this process for 100 years period in order to meet the increasing wood demand, we found that a significant amount of carbon stock (tC/ha) would be created and more atmospheric carbon would be sequestered in the forest. It was also observed that increases up to 5% of the harvested volume would be considerable to augment forest carbon stock (Figure 2b). Greater than 5% harvesting intensity would not be advantageous. For example, if increased by 10 %, the carbon loss from harvesting would be greater than the carbon balance after 50 year, and the net forest carbon balance (tC/ha) would start decreasing after that years. Thus the difference between carbon balance and carbon loss could play an important role in enhancing carbon stock per hectare. If the difference is positive, this indicates the sustainable forest management practice exists to sequester more atmospheric carbon. Otherwise, the management efforts would be oriented to accrue more biological carbon cycle and maximize carbon stock.

The mean carbon balance would be 1.16 tC/ha (Fig 2.3a) ranging from -3.41 to 6.13 tC/ha. At 95% confidence level, the net forest carbon balance would be between -2.53 tC/ha at 0.025 quantile and 4.83 tC/ha at 0.975 quantile. At 90% confidence level, the net carbon balance would be between -2.25 tC/ha at 0.05 quantile and 4.41 tC/ha at 0.95 quantile. If dead trees were treated as carbon loss and simulated along with carbon loss from removal and fire, the mean carbon balance would be -3.63 tC/ha with a range from -11.83 to 4.89 tC/ha (Fig 2.3b). At 95% confidence level, the net carbon balance would be between -9.32 tC/ha at 0.025 quantile and 2.31 tC/ha at 0.975 quantile. At 90% confidence level, the net carbon balance would range from -8.63 tC/ha at 0.05 quantile to 1.51 tC/ha at 0.95 quantile. Under this condition, there would be a higher possibility that the existing forest carbon balance could decrease.



**Figure 2.2 Predicted trends of carbon growth and carbon balance for 100 years:**

**(a) Carbon growth rate per hectare. (b) Cumulative carbon balance from stock and current carbon timber removal rate with the growth rate, constant timber volume removal rate and 5% increment in removal rate for a consecutive five year period.**



**Figure 2.3 Stochastic simulation of carbon balance from net stock and growth rate:**

**(a) Carbon balance includes timber removal and fire loss rate, (b) Carbon balance including timber removal, fire loss and net dead rate.**

### 2.3.2 Carbon Emissions from Timber Harvesting and Transportation

Carbon emission rates from consumption of fossil fuel was  $5.06 \pm 0.90$  tC/TCM using manual harvesting systems and  $6.84 \pm 1.22$  tC/TCM using mechanized harvesting systems with a hauling distance of 80 km or less. Mean carbon emission level from mechanized and manual harvesting systems was not significantly different ( $p = 0.058$ ) at 95% confidence level. It could be attributed to the similar fuel consumption and productivity rates for loading and hauling in both harvesting systems. Annual carbon emission was directly proportional to timber volume harvested (Table 2.2). Carbon emission in both harvesting systems was lower in contrast to the average carbon content level ( $296 \text{ kg/m}^3$ ) of timber harvested that is consistent with the carbon content of ( $307 \text{ kg/m}^3$ ) for hardwood round logs in the Northeast region (Skog and Nicholson, 1998).

Mean carbon emission of combined diesel and gasoline consumption did not significantly differ ( $p = 0.106$ ) while it was significantly different from lubricant consumption ( $p = 0.031$ ) between mechanized and manual harvesting systems. It was 6.06 and 4.61 tons/TCM from combined diesel and gasoline consumption and 0.65 and 0.45ton/TCM from lubricant consumption for the mechanized and manual harvesting systems, respectively. In carbon emission level from both harvesting systems, hauling process contributed greater percentage of carbon emission from diesel and gasoline consumption (Table 2.3). It was followed by felling and skidding in mechanized harvesting system, whereas it was followed by skidding and loading process in manual harvesting system. Similarly, skidding process contributed greater percentage of carbon emissions from lubricant consumption in both harvesting systems.

**Table 2. 2 Annual C emissions (in thousand tons) in harvesting mixed hardwood species.**

Fuel type	Machine	Year			
		2000	2006	2008	2009
<b>Manual Harvesting System</b>					
Diesel	*Chainsaw	0.941	1.219	1.220	0.854
	Cable skidder	9.804	12.696	12.710	8.895
	Larger Loader	8.190	10.605	10.617	7.430
	Long log truck	17.121	22.170	22.194	15.533
	Subtotal	36.056	46.689	46.741	32.711
Lubricant	Chainsaw	0.024	0.031	0.031	0.022
	Grapple skidder	2.961	3.834	3.838	2.686
	Larger Loader	0.157	0.203	0.204	0.143
	Long log truck	0.422	0.546	0.547	0.383
	Subtotal	3.564	4.615	4.620	3.233
<b>Total</b>		<b>39.619</b>	<b>51.304</b>	<b>51.361</b>	<b>35.944</b>
<b>Mechanized Harvesting System</b>					
Diesel	Feller-buncher	11.857	15.353	15.370	10.757
	*Chainsaw	0.792	1.026	1.027	0.719
	Grapple skidder	10.488	13.582	13.597	9.516
	Larger Loader	8.190	10.605	10.617	7.430
	Long log truck	17.121	22.170	22.194	15.533
	Subtotal	48.448	62.736	62.806	43.954
Lubricant	Feller-buncher	1.329	1.721	1.723	1.206
	Chainsaw	0.018	0.023	0.023	0.016
	Grapple skidder	3.142	4.068	4.073	2.850
	Larger Loader	0.157	0.203	0.204	0.143
	Long log truck	0.422	0.546	0.547	0.383
	Subtotal	5.068	6.563	6.570	4.598
<b>Total</b>		<b>53.516</b>	<b>69.299</b>	<b>69.376</b>	<b>48.552</b>

\* Chainsaw uses gasoline.

**Table 2. 3 C emissions from fossil fuel due to harvesting hardwood species by harvesting function.**

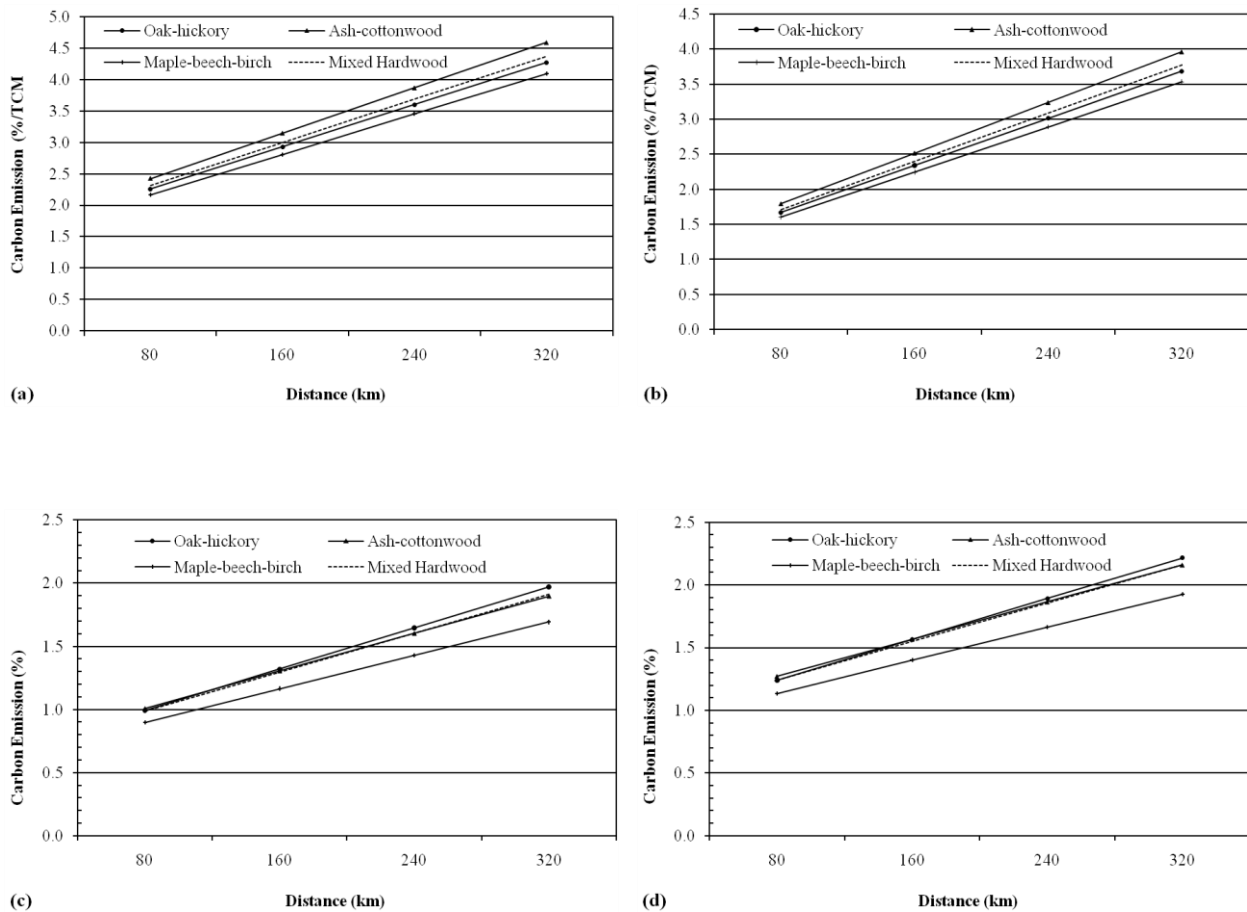
	Manual harvesting system		Mechanized harvesting system	
	Diesel (C %)	Lubricant (C %)	Diesel (C %)	Lubricant (C %)
*Felling	2.61	0.68	24.47	26.23
Processing			1.64	0.36
Skidding	27.19	83.08	21.65	61.99
Loading	22.71	4.41	16.90	3.10
Hauling	47.48	11.84	35.34	8.32

\*Felling process in manual harvesting consumes gasoline and topping and delimiting are also associated with it.

### 2.3.3 Carbon Displacement from Forest to Sawmill

Carbon stored in standing trees was displaced from timberland to sawmill or facilities at the expense of carbon emission from fossil fuel consumption of timber harvesting system. In the base case scenario (mixed hardwood) of mechanized harvesting, the forest carbon displacement rate was 2.31% of the carbon stored in harvested timber, while it was 1.71% of the carbon stored in the harvested timber using manual harvesting system. This variation in forest carbon displacement rate was due to higher carbon emission amount from mechanized harvesting system than manual harvesting system. As hauling distance increased, the carbon displacement rate also increased (Figure 2.4a and 2.4b). It was 4.37% and 3.77 %, respectively for hauling up to 320 km in mechanized harvesting and manual harvesting. Therefore, longer hauling distance could indirectly decrease the accountability of the carbon balance of the harvested timber to some extent. Forest carbon displacement rates also varied with the harvested volume of different forest types since the average carbon content by forest type varied. For example; the estimated carbon content of the harvested timber was 296, 282, 303 and 316/TCM for the base case (mixed hardwood), ash-cottonwood, and oak-hickory and maple-beech-birch forest type, respectively.

Therefore the forest carbon displacement rate was greater in ash-cottonwood forest type than that in the mixed hardwood types, but it was lower in maple-beech-birch forest type and followed by oak-hickory forest type (Figure 2.4a and 4b) in both harvesting systems.



**Figure 2.4 Carbon displacements of four different forest type from the timber harvesting systems and the generated residue extraction systems. (a) and (b) timber harvesting under mechanized and manual harvesting systems. (c) and (d) residue extracting under cable and grappler skidding systems.**

Approximately 265 m<sup>3</sup> (32 green metric tons/ ha) of logging residue was estimated for harvesting 1000 m<sup>3</sup> volume of mixed hardwood species. This estimate was 7 tons/ha greater to an

estimated of 25 tons/ha of wood residue availability in southern WV (Grushecky et al., 2007). In the base case, forest carbon displacement rate was 1% and 1.2% of the carbon stored in logging residue using a cable skidding system or a grapple skidding system, respectively. This difference was due to higher fuel consumption rate of grapple skidder than by cable skidder in the residue extraction process. The difference would be greater when hauling for a longer distance due to coupled effects of road types, i.e., 1.9% using cable skidder and 2.2% using grapple skidder for hauling up to 320 km (Figure 2.4c and 4d). The forest carbon displacement rate variation was also observed among forest types (Figure 2.4c and 4d). This variation was also coupled due to green weight of unchipped residue that limits truck payload size and increases trucking cycle time.

The forest carbon displacement varied for both harvesting system and residue extraction system due to the effects of carbon content of trees and their composition on the timber harvested volume for the respective forest types. Therefore, tree species with varied carbon content per unit volume, would play an important role in determining net carbon balance of harvested timber and forest carbon displacement rate from forest to sawmill. For example, yellow-poplar of 215 tons/TCM in Oak-hickory forest group, cottonwood of 205 tons/TCM in Ash-cottonwood forest group.

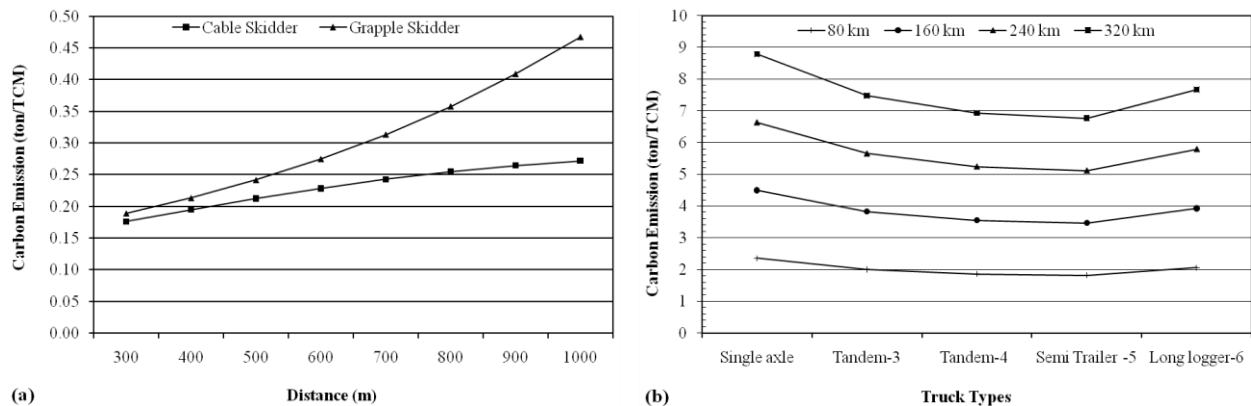
#### **2.3.4 Sensitivity Analysis and Uncertainty of Carbon Emission**

It was found that carbon emission (tons/TCM) increased with skidding distance (Figure 2.5a). Carbon emission from grapple skidder was sharply increased from 0.19-0.47 tC/TCM while carbon emission from cable skidder was gradually increased from 0.18 – 0.27 tC/TCM when the skidding distance changed from 300 to 1,000 m. In this regard, the use of a cable



skidder would be beneficial in avoiding certain amount of carbon emission from these harvesting systems.

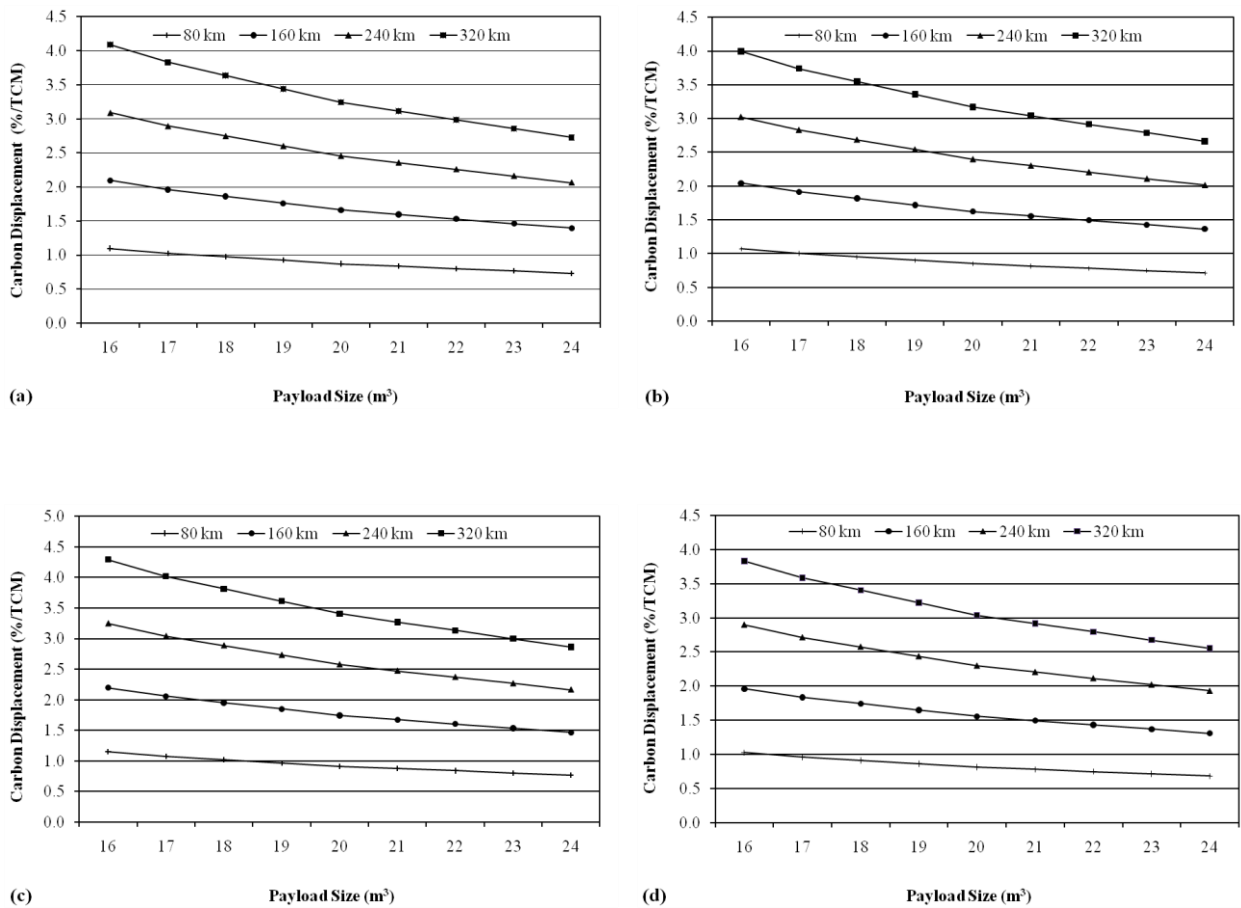
The amount of carbon emission (ton/TCM) varied with different hauling truck types. In the base case of 80 km, carbon emission tons/TCM was almost equivalent for all five trucks types. But when distance was increased up to 320 km, it was found that carbon emission per unit volume transported using a single axle truck was quite greater than that of other truck types (Figure 2.5b). A single axle truck has a smaller payload and the higher number of hauling cycle though it consumes less fuel compared to other trucks. The use of tandem-4 axle single truck or tractor-semi trailer-5 axle truck would be beneficial in minimizing carbon emissions amount from the hauling process at greater distances.



**Figure 2.5 Carbon emission variations during skidding and hauling of mixed hardwood species: (a) by skidder types and skidding distance (meters) and (b) by truck type and hauling distance (km).**

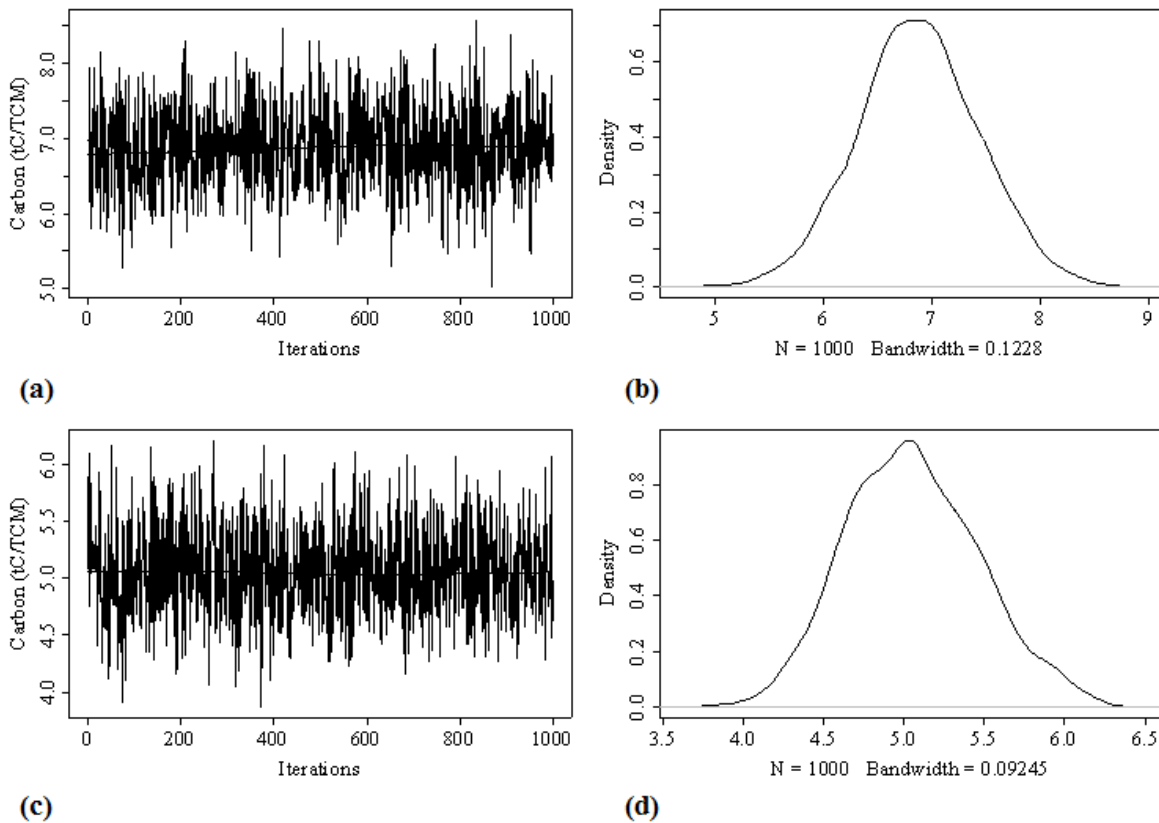
The amount of carbon emissions (tons/TCM) from the hauling process was also affected by truck payload size and hauling distance for different forest types. Trucking for a longer

hauling distance with smaller payload size would emit a greater amount of carbon (Figure 2.6a, 6b, 6c and 6d). However, average truck payload size is usually 5 m<sup>3</sup> less than the maximum payload, because log dimension, shape and log arrangement in a truck determine the payload size at volume rather than payload size at tons (Timson, 1974). Hence, greater carbon emissions would occur from hauling timber at lower payload size (18 m<sup>3</sup>) compared to a standard payload size (23 m<sup>3</sup>), which results in a carbon emission ratio of 1:1.27.



**Figure 2.6 Carbon displacement rate variations from hauling process by different payload size at different distances: (a) Mixed hardwood forest species (b) Oak-hickory forest group (c) Ash-cottonwood forest group, and (d) Maple-beech-birch forest group.**

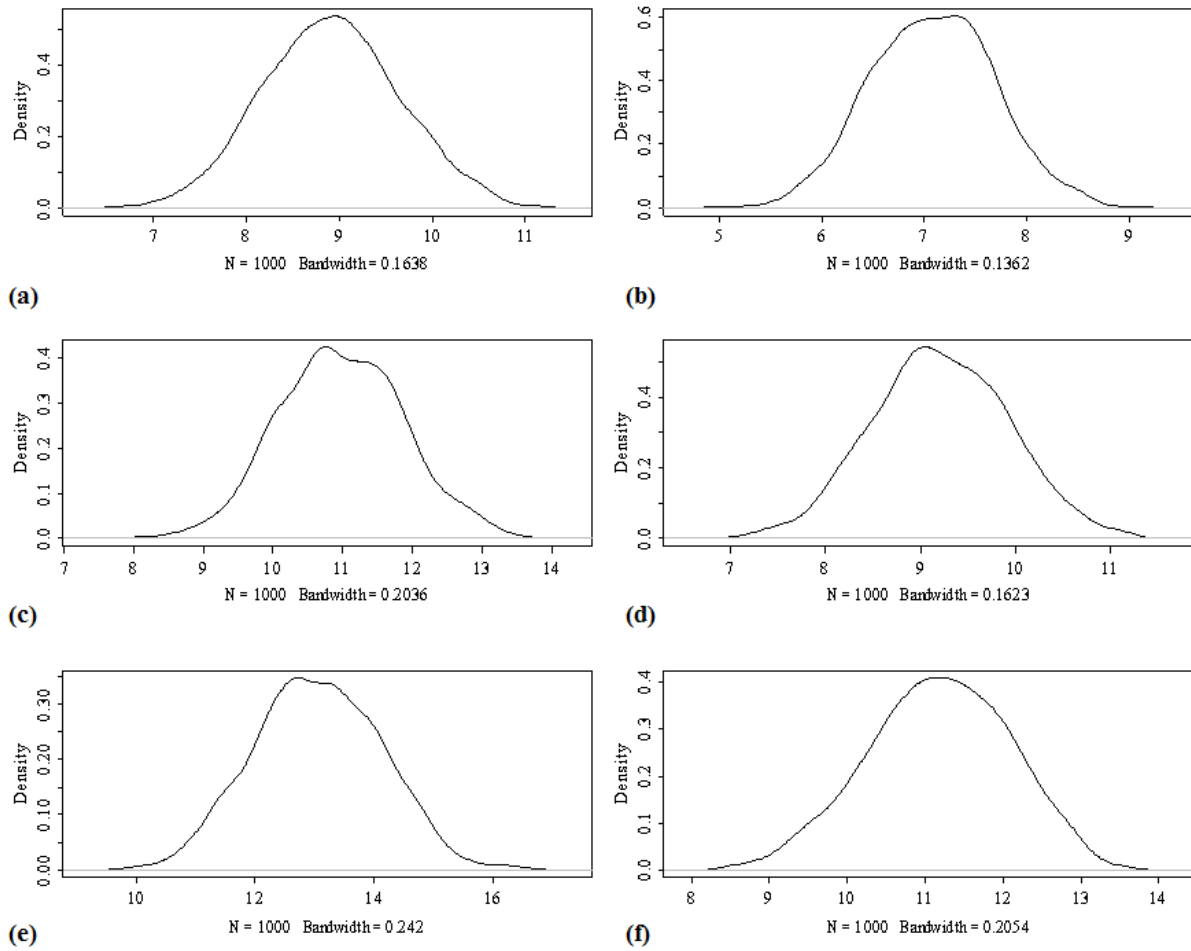
In the base case scenario of 80 km distance, a slight deviation in mean carbon emission level (tC/TCM) existed for both harvesting systems if it was iterated for 1,000 times (Figure 2.7a and 7c). For mechanized harvesting, mean carbon emission was  $6.87 \pm 0.56$  tC/TCM ranging from 5.78 to 7.93 tC/TCM (Fig 2.7b) with a higher probability density. For manual harvesting system, mean carbon emission was  $5.08 \pm 0.39$  tC/TCM ranging from 4.28 to 5.81 tC/TCM (Figure 2.7d). The mean carbon emissions of both harvesting systems was positioned at 50% quantile and was similar to the estimate (tC/TCM) under typical operational conditions for both systems.



**Figure 2.7 Trace plot and probability density plot of carbon emission (tC/TCM) using mechanized (a) and (b) and manual (c) and (d) harvesting systems in the base case scenario.**

In the scenario of hauling distance up to 160 km, the mean carbon emission was  $8.88 \pm 0.70$  tC/TCM and  $7.07 \pm 0.57$  tC/TCM at 50% quantile using mechanized and manual harvesting systems, respectively (Figure 2.8a and 2.8b). In this case, the uncertainty with respect to carbon emissions would range from 7.529 -10.22 tC/TCM for mechanized system and it would be 5.97 - 8.11tC/TCM for manual harvesting system at 2.5% and 97.5% quantile distribution, respectively. If hauling distance up to 240 km, the mean carbon emission was  $9.91 \pm 0.731$  and  $9.13 \pm 0.735$  tC/TCM at 50% quantile distribution for mechanized and manual harvesting systems, respectively (Figure 2.8c and 8d). In this case, the uncertainty for carbon emissions would range from 8.37 – 11.34 tC/TCM for mechanized system and 7.69-10.60 tC/TCM for manual harvesting system at 2.5% and 97.5% quantile distribution, respectively. Similarly using the hauling distances 320 km, the mean carbon emission was  $12.97 \pm 1.02$  tC/TCM and  $11.17 \pm 0.89$  tC/TCM at 50% quantile using mechanized and manual harvesting systems, respectively (Figure 2.8e and 8f). These had a range of carbon emissions from 11.03 to 15.06 tC/TCM and 9.47 to 12.99 for mechanized harvesting and manual harvesting at 2.5 % and 97.5% quantile distribution respectively.

The estimated uncertainty of carbon emission range would be useful in predicting the minimum and maximum level of carbon burden created by fossil fuel consumption by timber harvesting systems. The uncertainty of carbon emission levels from harvesting system would always be associated with the variation in a machine's productivity level (Wang et al., 2004a, 2004b; Oneil et al., 2010; Li et al., 2006) and hauling process (McCormark, 1990; Oneil et al., 2010). Higher production per machine hour would create smaller carbon emission burdens and vice versa with respect to fossil fuel consumption.



**Figure 2.8 Probability density of carbon emission (tC /TCM) using mechanized (a, c, e) and manual harvesting systems (b, d, f) at three different hauling distance i.e. 160 km (a, b), 240 km (c, d) and 320 km (e, f).**

## 2.4 Conclusions

Estimation of forest carbon balance considering carbon loss from dead trees and forest fire along with timber removal rate helps to predict future carbon balance of the timberland. Forest carbon removal due to harvesting, small fire and limited dead trees does not significantly impair the existing forest carbon stock. However, an increase in the number of dead trees or harvesting intensity could reduce the net carbon balance of timberland. Considering rotation age of the natural mixed hardwood forests with slight increase in harvesting intensity, would also increase forest carbon stock, meet wood supply demands and undermine carbon emissions from fossil fuel consumption. Such practice would have healthy impacts on the carbon stock for timberland and neutralize minor natural depreciation of carbon from fire loss and dead trees.

Natural regeneration in forests, as applicable in the Appalachian region, entails no fossil fuel consumption in seedling production and plantation and thus results in zero carbon emission level from mechanized instrument. Although mechanized harvesting systems emit more amount of carbon into the atmosphere than manual harvesting systems, the mean carbon emissions amount do not differ significantly between these two harvesting systems. The amount of carbon emissions from fossil fuel consumption due to harvesting is considerably lower than the carbon stored in the harvested timber and logging residue. Harvesting functions such as felling, skidding, topping and delimiting and loading present less effect on carbon emissions compared to hauling. Hauling distance and truck payload size also influence carbon emissions amount, which increases the forest carbon displacement rate and reduce the carbon balance in harvested timber. The uncertainty of carbon emissions amount and the carbon balance of harvested timber also depend on the harvested volume of different forest types and the machine's productivity for each process.

## References

- Alden, H. A. 1995. *Hardwoods of North America*. Gen. Tech. Rep. FPL–GTR–83. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 136 p.
- Bonnicksen, T.M. 2008. Greenhouse gas emissions from four California wildfires: opportunities to prevent and reverse environmental and climate impacts. FCEM Report 2. The Forest Foundation, Auburn, California. 19 p.
- Brinker, R. W, Kinard, J., Rumber, B. and Landford, B. 2002. Machine rates for selected forest harvesting machines., Alabama Agricultural Experimental Station, Auburn University, Circular (Revised), September 2002 p -3-30.
- English, B., Jensen, K., Park, W., Menard, J., and Wilson, B. 2000. The wood transportation and resource analysis system (WTRANS): Description and Documentation and User's Guide for WTRANS. Department of Agricultural Economics, University of Tennessee, p 1-32.
- Dixon, R. K., S, Brown., R. A., Houghton, A. M., Solomon, M. C. Trexler, and J. Wisniewski. 1994. Carbon pools and flux of global forest ecosystems. *Science*. 263:185-190.
- Grushecky, S. T., Wang, J., and McGil, D. W. 2007. Influence of site characteristics and costs of extraction and trucking on logging residue utilization in southern West Virginia. *Forest Products Journal* Vol 57, No. 7/8 pp 63-67.
- Gower, S. T. 2003. Patterns and mechanisms of the forest carbon cycle. *Ann. Rev. Environ. Resour.* 28, 169–204.
- Harmon, M. E. 2001. Carbon sequestration in forests: Addressing the Scale Question. *Journal of Forestry*, Volume 99, Number 4, 1 April 2001, pp. 24-29(6)

- Harouff, S. E., Grushecky, S. T., and Spong, B. D. 2008. West Virginia forest industry transportation network analysis using GIS. Proceeding of the 16<sup>th</sup> Central Hardwoods Forest Conference, GTR NRS-P-24 pp 257-264.
- Hennigar, C. R., MacLean, D. A. and Amos-Binks, L. J. 2008. A novel approach to optimize management strategies for carbon stored in both forests and wood products Forest Ecology and Management 256 (2008) 786–797
- Husqvarna, 2002. Operator's manual (EPA) 55 Rancher.  
[http://weborder.husqvarna.com/order\\_static/doc/HOUS/HOUS2002/HOUS2002\\_1140106-95.pdf](http://weborder.husqvarna.com/order_static/doc/HOUS/HOUS2002/HOUS2002_1140106-95.pdf), pg 1-35
- INRS, 2007. Innovative Natural Resource Solutions LLC, Biomass availability analysis-Five counties of Western Massachusetts. Prepared for Massachusetts Division of Energy Resources & Massachusetts Department of Conservation and Recreation. p 55.
- IPCC, 2006a. Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T., and Tanabe K. (eds). Published: IGES, Japan. Vol.2 Energy, Chapter 3, pp 78.
- IPCC, 2006b. Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan. Vol. 4 AFOLU, Chapter 4, pp. 83.
- ISO, 2006. Environment management – Life cycle assessment- Requirements and guidelines. International Organization for Standardization (ISO 14044:2005[E]) 54 pp
- Janisch, J. E. and Harmon, M. E. 2002. Successional changes in live and dead wood carbon stores: implication for net ecosystem productivity. Tree Physiology (2002), 22, 77-89



- Li, Y., Wang, J., Miller, G, and McNeel, J. 2006. Production economics of harvesting small-diameter hardwood stands in central Appalachia. *Forest Products Journal* 2006, Vol 56, No. 3 pp 82.
- Lippke, B., Wilson, B., Meil, J., and Taylor, A. 2010. Characterizing the importance of carbon stored in wood products. *Wood and fiber science*, March 2010 V. 42, pp 5-14.
- Mason C.L., Casavant K L, Lippke BR, Nguyen DK, and Jessup, E. 2008.. The Washington log trucking industry: Costs and safety analysis. Report to the Washington State Legislature 2009. pp 125
- McCormack, R. J. 1990. Measuring and evaluating log truck performance in a variety of operating conditions. PhD. dissertation, Virginia Polytechnic Institute and State University, Blacksburg, Virginia. 138 p.
- Milauskas, S. J., and Wang, J. 2006. West Virginia logger characteristics. *Forest Product Journal* Vol 56, No 2, pp 24.
- Oneil, E. E., Johnson, L. R., Lippke, B. R., McCarter, J. B., McDill, M. E., Roth, P. A., and Finley J. C. 2010. Lifecycle impacts of inland and northwest and northeast/north central forest resources. *Wood and fiber science*, March 2010 V. 42(CORRIM special issue) pp 29-51.
- Petit, J. R., Jouzel, J., and Raynaud, D. P. Y. 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* 399:429-436.
- Perez-Garcia, J., Lippke, B., Briggs, D., Wilson, J., Bowyer, J., and Meil, J. 2005. The environmental performance of renewable building materials in the context of residential construction. *Wood Fib. Sci.* 37, 3–17

- Perlack, R. D., Wright, L. L., Turnhollow, A. F., Graham, R. L., Stokes, B. J., and Erbach, D. C. 2005. Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. Oak Ridge, TN: Oak Ridge National Laboratory. 59 p.
- Puettmann, M. E., Bergman, R., Hubbard, S., Johnson, L., Lippke, B., Oneil, E., and Wanger, F. G. 2010. Cradle to gate life cycle inventory of US products production: CORRIM phase I and phase II products. Wood and fiber science, March 2010 V. 42, pp 16-28.
- Raupach, M.R., Marland, G., Ciais, P., Quéré, C.L., Canadell, J. G., Klepper, G. and Field, C. B. 2007. Global and regional drivers of accelerating CO<sub>2</sub> emissions. Proceedings of the National Academy of Sciences of the United States of America 104:10282-10287
- Richards, K.R., Alig, R., Kinsman, J.D., Palo, M. and Sohngen, B. 1997. Consideration of country and forestry/landuse characteristics in choosing forestry instruments to achieve climate mitigation goals. Critical Reviews in Environmental Science and Technology, 27 pp 47-64.
- Schlamadinger, B., and Marland, G. 1996. The role of forest and bioenergy strategies in the global carbon cycle. Biomass Bioenergy 10, 275–300.
- Skog, K .E. and Nicholson, G .A. 1998. Carbon cycling through wood products: The role of wood and paper products in carbon sequestration. Forest Product Journal 48:75-83.
- Sharma, B.D. 2010. Modeling of forest harvest scheduling and terrestrial carbon sequestration, Ph.D. dissertation, West Virginia University, Morgantown, WV.
- Sharma, B.D., Wang, J., and Liu, S. 2011. Modeling of sustainable biomass utilization and carbon emission reduction in West Virginia. Sensor Letters Volume 9: 1175-1179.

- Smith, J. E., Heath, L. S., Skog, K. E., and Birdsey, R. A. 2006. Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.
- Spong, B. 2007. Laws and regulation for West Virginia loggers. Charleston, WV; West Virginia Division of Forestry, 85 p.
- Straka, T. J., and Layton, P. A. 2010. Natural Resources Management: Life cycle assessment and forest certification and sustainability issues. [www.mdpi.com/journal/sustainability](http://www.mdpi.com/journal/sustainability), Sustainability 2010, 2, 604-623.
- Timson, F.G. 1974. Weights and volume variation in truckloads of logs hauled in the central Appalachians. USDA Forest Service Research Paper, NE-300, 1-9.
- USDA FS, 2006. Forest inventory and analysis National core field guide Volume I: field data collection procedures for phase 2 plots. Version 3.1 Northern Edition, 1-294
- USDA FS, 2010. Forest Inventory Data Online Version. 2.0. US Department of Agriculture. Forest Service. Available online at <http://fiatools.fs.fed.us/fido/index.html> (accessed on Jan 20, 2011).
- USEPA, 2010. Environmental Protection Agency (EPA). Inventory of US greenhouse gas emissions and sinks: 1990-2008, April 15, 2010, pp 407.
- USEPA 2005. Emission Facts, Average carbon dioxide emissions resulting from gasoline and diesel fuel. EPA420-F-05-001 February 2005 pp. 2.
- Vannien, P. and Makela, A. 2004. Carbon budget for Scots pine trees: effects of size, competition and site fertility on growth allocation and production. *In* Tree Physiology 25, 17–30 © 2005 Heron Publishing—Victoria, Canada, published online November 1, 2004

- Wang, J., Long, C., McNeel, J., and Baumgras, J. 2004a. Productivity and cost of manual felling and cable skidding in central Appalachian hardwood forests. *Forest Products Journal* vol. 54, No. 12 pp 45-51.
- Wang, J., Long, C., and McNeel, J. 2004b. Production and cost analysis of a feller-buncher and grapple skidder in central Appalachian hardwood forests. *Forest Products Journal* vol.54 No. 12 pp 59-67.
- WVDOP [West Virginia Division of Forestry]. 2010. Fire statistics from recent years (<http://www.wvforestry.com/dailyfire.cfm>) accessed on June 25, 2010
- White, M. K., Gower, S. T., and Ahl, D. E. 2005. Life cycle inventories of roundwood production in northern Wisconsin: Inputs into an industrial forest carbon budget. *Forest Ecology and Management* 219, pp 13–28

### **3. CARBON BALANCE ANALYSIS OF HARDWOOD LUMBER PROCESSING IN CENTRAL APPALACHIA<sup>2</sup>**

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<sup>2</sup> To be submitted to Forest Products Journal

## **Abstract**

Hardwood lumber processing generates mill residue and consumes energy, such as electricity and fossil fuels, which eventually increases atmospheric carbon and creates credit carbon balance. This study assessed credit carbon emission and carbon balance from lumber processing of different size sawmills and its effect on the potential carbon offsetting capacity through product useful life. Data were obtained from a regional sawmill survey, public database and relevant publications. Credit carbon balance was statistically analyzed within the gate to gate life cycle inventory framework. Stochastic simulation of carbon emission and its impact on carbon balance and carbon flux from lumber processing was carried out under different sawmill operational scenarios. Credit carbon balance from electricity consumption was significantly different among sawmills of different production levels and operation hours per week. Variation in carbon emission was also recognized due to different head saws, lighting types and air compressors used at sawmills. Generated credit carbon balance in significant amounts from energy source consumption reduced carbon accountability of the lumber in its useful life period at first order of decay of carbon. This credit balance would also affect wood carbon disposition patterns in hardwood sawlogs. Substantial amount of carbon flux occurred due to greater amount of energy consumption and exports of lumber would also reduce carbon accountability of lumber production. Carbon storage accountability of hardwood lumber could be improved by reducing carbon flux from processing using an efficient equipments at sawmill and as well as an appropriate mixture of energy sources for electricity supply.

### 3.1 Introduction

The forest carbon cycle and net carbon budget are influenced by the wood product cycle as carbon emissions occurs throughout forest product life span (Apps et al. 1999; Gower, 2003; White et al., 2005). Wood products are carbon reservoirs and limit sequestered carbon emission into the atmosphere, depending on the type and useful life period of these products (Row and Phelps 1996; Skog et al., 2004). Long living wood products act as a carbon pool, create a lag time in carbon release and determine the rate of carbon return to the atmosphere (Karjalainen et al., 2002). Sustainable wood products in use serve as an important carbon pool in sequestering carbon that would otherwise be released into the atmosphere and contribute to climate change (Dixon et al., 1994). Additionally they replace other fossil fuels and energy after their service life or decay in landfills (Werner et al. 2005).

Carbon (C) stocks of wood products can be useful in evaluating their potentials in GHG mitigation (Brown et al., 1998; IPCC, 2003). Carbon tracking in wood products requires knowledge of life cycle for realistic estimation and statistical representation of potential amount of carbon contained in wood. Most estimates of C stocks and stock changes are based on indirect estimation models using hypothetical parameters (Kurz et al., 1992; Harmon et al. 1994; Apps et al. 1999). One of the approaches to estimating C pools in wood products is accounting for the amount of carbon expected to be stored in wood products and in landfills at the end of a 100-year period (Skog et al. 2004; Smith et al., 2006; Birdsey, 2006). Estimation of C in wood products can start from the quantity of roundwood that is harvested, removed from the forest and available to primary processing for wood products in the mills (Birdsey, 2006). Carbon emission estimation of wood products during their life time is affected by the decay rate and fraction of carbon allocated to long-lived products (Dias et al., 2005; Smith et al., 2006). Wood decay rate

also influences the estimate of the carbon pool and uncertainty of outflow (Winjum et al., 1998). The C estimation is also affected by waste treatment practices that influences C sink (Micales and Skog, 1997; Pingou et al., 1996). One way of diminishing the uncertainty of the C pool estimates is to perform direct stock inventories of wood products (Pingoud et al., 2001).

In wood product manufacturing, greenhouse emissions occur from the use of energy sources at different processing stages and uses over its life cycle. Normally, it occurs from manufacturing process, mill residue process and transportation. According to an EPA report, the growth rate in GHG emissions from 1990 to 2008 is weighted an average of 1.8% from electricity consumption, 0.8% from fossil fuel consumption 0.8% and 0.9% from energy consumption (USEPA, 2010a). The amount of carbon emission from the consumption of different energy sources, such as coal, fossil fuels, petroleum, is different because of their different heating value and carbon coefficients (US EPA, 2010a, 2010b; USEIA, 2011). The mean heating value of these products changes with time depending on the composition (coal), the blend of primary ingredients (petroleum products) and impurities (natural gas). This variation of carbon emission amount over the course of a year from these different fuel sources leads to change in an annual cycle in the carbon isotope ratio (Blasing, 2005).

In a life cycle inventory (LCI) measure of total energy required, the degree of energy required for a product varies based on the wood product type. The energy requirement in manufacturing one m<sup>3</sup> of logs is greater than that for the same volume of logs in harvesting and transportation (Lippke et al., 2010). In a LCI of cradle to mill gate analysis, Puettmann et al. (2010) reported that hardwood lumber manufacture consumes 62% of the total energy but the energy consumption of hardwood flooring was even higher in the northeast region. Lumber processing requires large amount of saw logs and concurrently significant amount of wood loss



occurs in producing 1 m<sup>3</sup> dry lumber (Wilson and Dancer, 2005; Bergman and Bowe, 2008).

Wood loss occurred at each steps of a production chain as a percentage of carbon in the standing tree or harvested wood volume helps to portray the carbon losses at each step (Ingerson, 2009).

The guideline on fraction of carbon disposition in wood product is helpful in estimating the wood carbon loss during timber processing (Smith et al., 2006).

Log processing involves; yarding, debarking and bucking, drying and seasoning, and planning process that uses different types of mechanical equipments and consumes different type energy sources. Employed mechanical equipments such as head saw, and air compressors and sawmill management strategies such as production capacity, and lighting bulbs could play an important role in determining carbon emission level at sawmill. Such possible variation in carbon emission level “credit carbon” from the mechanical instruments, energy sources at sawmill production capacity was overlooked in the previous studies of LCI of wood product processing. Additionally, such credit carbon is also disregarded while accounting the carbon stored by the produced wood product in its useful life period. Therefore, this study aims to assess the carbon balance of hardwood lumber processing from sawmill size within the ‘gate to gate’ life cycle inventory framework. The specific objectives of this study were to: (1) assess the credit carbon balance generated from energy consumption at sawmill size and affect of efficient equipments in carbon emission level, and (2) examine the effect of credit carbon in the carbon accountability of the product in its useful life period.

## **3.2 Methodology**

### **3.2.1 Methodological Framework and System Boundary**

The debit and credit balance accounting principal was used to account for carbon emission as greenhouse gas emission, irrespective of other gaseous emissions. The amount of carbon, in metric tona (tC) stored in one thousand cubic meters (TCM) of planed dried lumber was assumed as an assets, since it increases the carbon stock of humanly assisted wood carbon pool. This increase wood carbon stock at the expense of carbon emissions from the electricity consumption, was considered as credit carbon balance. Carbon emissions were quantified based upon the quantity of carbon dioxide (44 molar mass) emissions using (12/44) factor value (USEPA, 2005). Carbon stored in green hardwood logs was defined as initial carbon stock as an is asset, i.e. debit carbon balance. Carbon emission from the use of energy sources, such as electricity, gas, and diesel, were accounted as liabilities, i.e. credit carbon balance. Carbon emission from mill residues such bark, chips, and sawdust were regarded as carbon loss as expense, i.e. credit carbon balance. The carbon stored in the final product of planed sawn lumber was regarded as net debit carbon balance accounting against the credit carbon balance from energy consumption.

This process begins with the green hardwood logs at the sawmills yards and ends with the final product of planed dried sawn lumber within the ‘gate to gate’ life cycle inventory framework (Figure 1). The system boundary and the process unit were defined as described by the National Renewable Energy Laboratory Life Cycle Inventory (NREL, 2010) database that covers the processing of green hardwood logs at a sawmill, kiln drying of rough sawn hardwood lumber and planing of kiln dried sawn lumber. Data on lumber production capacity, mill residue, energy consumption and energy efficiency practices in Appalachian sawmills were obtained

from a mail survey in 2010. A total of 58 sawmill from Pennsylvania, New- York, Ohio and West Virginia responded to the mail survey. Sawmills were classified into three categories based on their weekly production: (1) small sawmills (SSM): less than  $94.4\text{m}^3/\text{week}$  ( $\leq 40000$  bdf/week); (2) medium sawmills (MSM) :  $> 94.4$  and  $\leq 471.9\text{ m}^3/\text{week}$  ( $>40000$  and  $\leq 200000$  bdf/week); and (3) large sawmill (LSM) :  $> 471.9\text{ m}^3/\text{week}$  ( $>200,000$  bdf/week).

The required volume of green hardwood logs to produce  $1\text{m}^3$  of kiln dry planed lumber was obtained from a final report on hardwood lumber production in the northeast region (Bergman and Bowe 2008). Similarly, data on energy consumption and lumber production were also used to simulate and compare the results obtained from our survey. The survey response was not detailed enough to allocate the consumption of different energy sources in producing lumber to the lumber production process i.e. debarking, lumbering and drying, but it provided the average monthly electricity consumption rate. Similarly, natural gas consumption in sawmill was also reported by a few responses.

### **3.2.2 Carbon Emission from Energy Sources**

Average monthly electricity consumption reported in kWh/month and the consumption rate reported in dollars was normalized to MJ/month based on the industrial average monthly bills and state data by US Energy Information Administration (USEIA, 2010) (Table 5). Carbon emission (tC/TCM) from electricity consumption (MJ/TCM) was estimated using an average emission factor for mixed energy sources reported by the US Environment Protection Agency (USEPA, 2010b) on emission and generation resource integrated database (eGrid) for the regions of RFC WEST (WV & OH), RFC EAST (PA) and NYUP (NY) in 2004, 2005, and 2007. Carbon emission from the mixed energy sources such as fossil fuel, coal, oil and gas were

assumed to have an average of 0.17 kg/MJ (USEPA, 2010b). Carbon generated from energy sources, such as natural gas, propane, fuel #1, fuel #4 and fuel #6 was estimated using the national average carbon dioxide coefficient reported by USEIA (2011). Similarly, carbon emission from diesel and gasoline was estimated based on published emission facts by USEPA (2005). Energy gained from wood source was excluded assuming that it was substituted by mill residue generated from lumber processing at sawmill and to avoid double quantification of carbon stock. Other related carbon emissions amount from electricity consumption (*EC*) from offsite generation and onsite generation and all energy sources (*ES*) used in lumber processing was based on the CORRIM report (Bergman and Bowe 2008) (Table 3.1).

**Table 3. 1 Carbon emission from all energy sources.**

Energy source	Consumption Rate	SI unit per 1 m <sup>3</sup>	Carbon emission per 1000 m <sup>3</sup>
Natural Gas	16.4	m <sup>3</sup>	8.62 Kg
Fuel #1	0.02	L	14.63 Kg
Fuel #2	2.08	L	1521.05 Kg
Fuel# 6	0.01	L	8.50 Kg
Propane	1.477	L	610.81 Kg
Electricity : Offsite generation	597	MJ	28040.91 Kg
Electricity : Onsite generation	10.2	MJ	479.09 Kg
Off-Road Diesel	6.65	L	4862.99 Kg
Gasoline	0.571	L	366.55 Kg
<b>Total</b>			<b>35913.15 Kg</b>

**Note:** Carbon emission was estimated at higher heating values of energy sources.

Carbon emissions (tC/TCM) from electricity consumption in lumber processing for different sized sawmill were simulated for 1,000 times using a known variance (normal likelihood) and assuming a conjugate normal prior mean. The uncertainty of carbon emission levels was examined using Markov-chain Monte Carlo (MCMC pack) simulation in R. Scenario

analysis of carbon emission from electricity source in eGRid sub region was carried out assuming coal, gas, oil and other fossil fuels are the major source of electricity generation. Though, nuclear and renewable sources shares significant percentage in electricity generation we didn't include assuming these sources is neutral to greenhouse gas emission. An average electricity generation shared percentage by the four energy sources from 2004 2005 and 2007 were proportioned to the total quantity of electricity generated. The base case was of mixed current source shared by coal (78.1%), gas (16%), oil (4.9%), and other fossil fuels (1.1%). Other scenarios of mixed sources of electricity in the eGrid sub-region include: Scenario 1 (RFC WEST) - coal (95.5%), natural gas (3.1%), oil (0.5%) and other fossil fuel (0.8%); Scenario 2 (RFC East)-, coal (75.2%), natural gas (18.4%), oil (4.8%) and other fossil fuel (1.5%); and Scenario 3 (NYUP) - coal (52..5%), natural gas (34.9%), oil (11.8%) and other fossil fuel (0.8%).

### **3.2.3 Carbon in Lumber and Mill Residue**

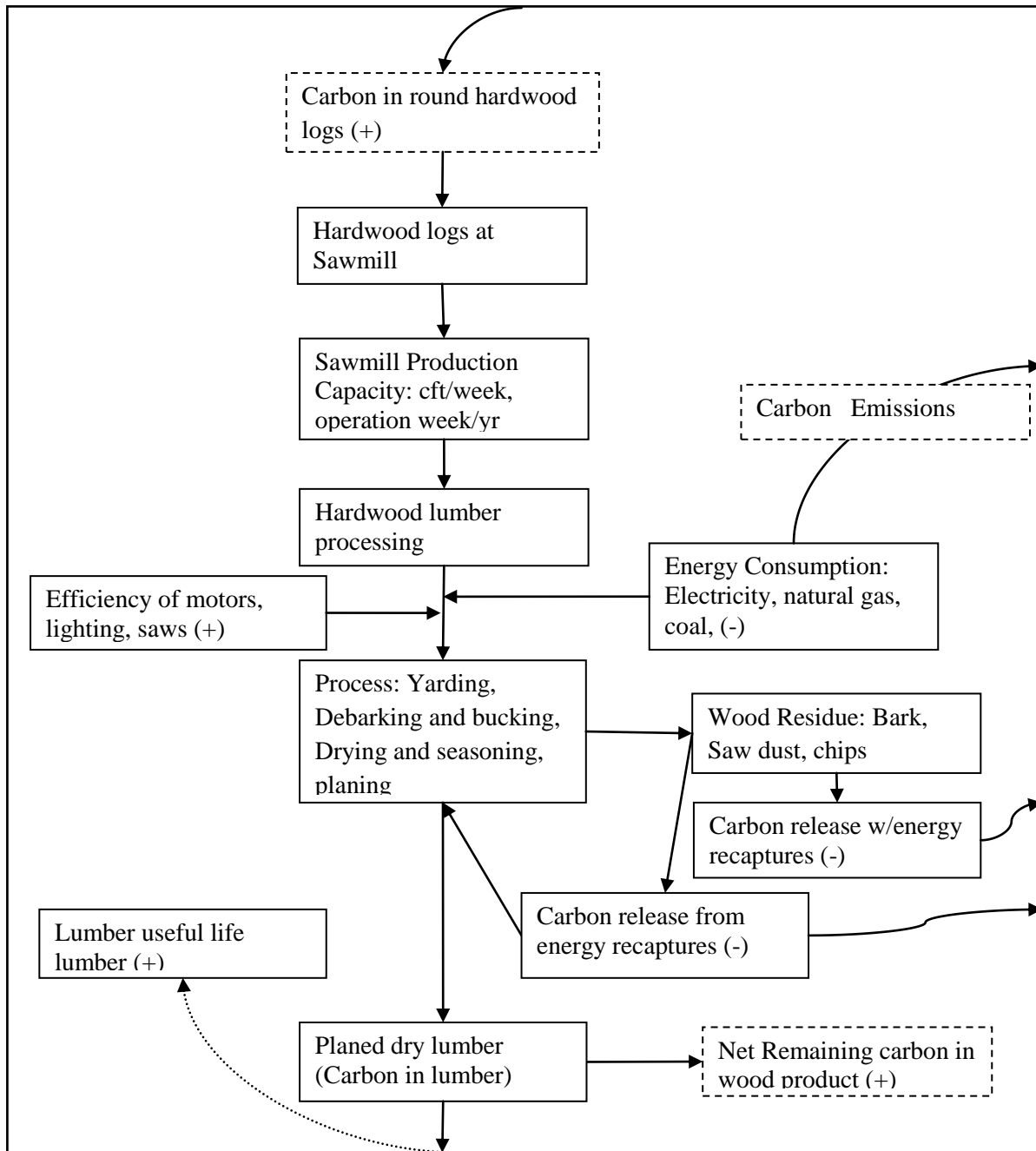
Wood loss occurred during lumber processing was accounted as a percentage of carbon stored in green hardwood logs at sawmill yard. Carbon stored in green hardwood logs was estimated at oven dry stage. An average of 296 kg of carbon was contained in one cubic meter of logs for the central Appalachian mixed hardwood species (Saud, 2011). A similar value of 307 kg/m<sup>3</sup> was used for carbon for round wood in the northeast region (Skog and Nicholson, 1998) and 260 kg/m<sup>3</sup> was used for both hardwood roundwood and hardwood lumber for the Unites States (Skog 2008). In hardwood lumber processing, volume shrinkage changed from 1.46 m<sup>3</sup> of green lumber to 1.37 m<sup>3</sup> of dried lumber (Bergman and Bowe, 2008) and carbon per unit also differs in wood products (Skog, 2008). Therefore, we assumed 315 kg/m<sup>3</sup> of carbon per unit

volume of planed dried lumber. Mill residues such as chips and sawdust (reported in green tons ) were assumed to contain 50% moisture, and were then converted to dry tons (Siau, 1984).

Carbon content of mill residue was assumed to be similar to saw logs.

The impact of carbon emission ( $C_{emission}$ ) from electricity at sawmills and from other energy sources on the fraction of carbon ( $j$ ) in lumber ( $FC_{lum}$ ) over its useful life period of 100 years ( $n$ ) was analyzed. For this, credit carbon pay off period ( $PP$ ), equation 3.1, was estimated.  $PP$  is the time when the amount of carbon emission/credit carbon balance equivalent to the fraction of carbon in lumber at year  $i$ . This payoff period was estimated under half life scenario at first order of decay rate of carbon of hardwood lumber and the carbon disposition rate of industrial roundwood in the northeast region respectively (Smith et al., 2006) (Tables 6 and 9). Similarly, affect of carbon emissions from the average of all sawmill energy source consumption was analyzed for the carbon disposition pattern in sawlogs over the 100-year period.

Carbon flux from lumber processing was also analyzed considering the carbon emission from energy consumption, export of lumber and carbon loss from mill residues at sawmills. Similarly, four different scenarios of carbon flux ( $CF$ ) from energy ( $CF_{energy}$ ), export of lumber ( $CF_{export}$ ) and  $FC_{lum}$  from lumber production, for a 100-year period were analyzed. Cumulative carbon balance in lumber ( $CCB_{lumber}$ ) (Eq. 3.2), cumulative carbon emission from energy ( $CCF_{energy}$ ) (Eq. 3.3), cumulative carbon flux from export ( $CCF_{export}$ ) (Eq3.4) were used to estimate cumulative carbon flux ratio ( $CCFR$ ) (Eq. 3.5). The base case includes carbon flux from the average energy consumption and the average export of the lumber from sawmills. Other scenarios for  $CCFR$  were; (1) export and all  $ES$  consumption (2) export and 25% reduction in carbon emission or in all  $ES$  consumption, and (3) export and 50% reduction in carbon emission or all  $ES$  consumption.



**Figure 3. 1 Methodological framework and system boundary using LCI method.**

*Note: -minus sign denotes credit carbon balance and + sign denotes debit carbon balance*

$$PP = C_{emission} \cong FC_{lum_i} \quad (3.1)$$

$$CCB_{lumber} = \sum_{i=0, j=0}^{n=100} (FC_{lum_{i,j+n}} + FC_{lum_{i+1,j+n}} + \dots + FC_{lum_{i+n,j+n}}) \quad (3.2)$$

$$CCF_{Export} = \sum_{i=0}^{n=100} CF_{export_i} \quad (3.3)$$

$$CCF_{Energy} = \sum_{i=0}^{n=100} CF_{energy_i} \quad (3.4)$$

$$CCFR = \frac{(CCF_{Export} + CCF_{Energy})}{CCB_{lumber}} \quad (3.5)$$

### 3.2.4 Avoided Carbon Emission

Carbon that is not emitted from electricity consumption for lumber processing is regarded as avoided carbon emission. Typically, it is attributed to sawmill management that includes using efficient electric motors, upgrading efficient equipment such as head saws, air compressor, and lighting bulbs. Based on the machine's engine's capacity (*hp*), load factor (*lf*), utilization factor (*Uf*) and yearly operating hours (*Oh*), estimated energy usages (*ER*) can be reduced to 2% -5% using the Motor Master+ software (Gopalakrishan et al., 2008). However, the energy saving efficiency achieved can be up to 10-15% by identifying the most efficient action for a given repair or motor purchase decision at medium sized and large industrial facilities (USDOE, 2010).

Energy saving was estimated with reference to the wood industry assistance program focusing on IOF WV priorities (Gopalakrishan et al., 2008). The base case of a typical sawmill includes 1 air compressor (60 hp), 1 band saw (200 hp), 1 band saw (250 hp), 1 debarker (50 hp),



1 chipper (200 hp), 1 edger (50 hp), 8 trim saws (7 hp), 4 vibrators (7 hp), 1 crane chain (50 hp) and 2 log decks (20 hp). Avoided carbon emission scenario was analyzed at 2% and 5% energy saving with a range of 0.6 to 0.9 for both machine usage and load factors. Based on the above data and operation hours for sawmills, we estimated the potential avoided carbon emission amount from electricity saving. The total energy usage of the manufacturing system can be estimated using Equation (3.6) (Gopalakrishnan et al., 2008).

$$ER = Hp * 0.746 * Lf * Uf * Oh \quad (3.6)$$

*0.746 converts hp into kilowatts*

### 3.2.5 Sawmill Processing Assessments

Our survey responses were classified into categorical data and parametric data and were analyzed according to sawmill size. The categorical data such as response on use of efficient techniques and upgrading motors were analyzed in SPSS using crosstab.

Parametric (ratio and interval) data analysis was conducted in R. 2.9.2. Two-way Analysis of Variance (ANOVA) was conducted at a 95% confidence level to examine whether significant difference exist in mean monthly electricity consumption, mean operation hours per week and mean lumber production per week among different size sawmills. Further, post-hoc test, Tukey's Honestly Significant Difference (HSD) multiple comparison of mean was used to detect how difference exists among pairs of sawmills sizes at a 95% family wise confidence level. A linear regression model was fitted to predict yearly sawmill C emissions (metric tons) ( $CE_{sm}$ ) during the lumbering process through electricity consumption. The carbon emission based rate, based on average monthly electricity consumption rate, was interpolated into yearly

carbon emission values. Parameters, such as lumber production per week ( $lum_w$ ) in  $m^3$ , operating weeks per year ( $Opweek_{yr}$ ) and operating hours per week ( $Ohr_{wk}$ ), were used and tested at a 95% significance level.

Random effect of the use of efficient techniques in the carbon emissions amount from lumber processing was also analyzed by sawmills size. Specifically, a linear mixed effect model was employed for the carbon emission per TCM of lumber which depends on the main effect of sawmills size as the fixed effect. Random effect of the head saw types, lighting bulb types, and air compressor type was introduced and adjusted to the intercept as well as to sawmill size, in each model.

### **3.3 Results and Discussion**

#### **3.3.1 Carbon Emission from Electricity Consumption**

Sawmills were operated with an average of 34.8, 40.4, 42.7 hours per week with one shift in small sawmills (SSM), medium sawmills (MSM) and large sawmills (LSM), respectively. Similarly, the yearly average operation weeks were 47.46 for SSM and 50.4 weeks for both MSM and LSM. Consequently, electricity consumption rate was different among sawmills size with different production capacity (Table 3.2). The mean carbon emission from electricity consumption was 23.96, 11.03 and 0.87 tC/month for LSM, MSM and SSM, respectively. Therefore, carbon emission from lumber production was 9.01, 17.51 and 9.40 tC/TCM in LSM, MSM and SSM, respectively. The lower carbon emission in LSM might be attributed to the higher lumber production level and the use of efficient electric motors in these larger sawmills.

**Table 3. 2 Descriptive statistics of lumber production and electricity consumption.**

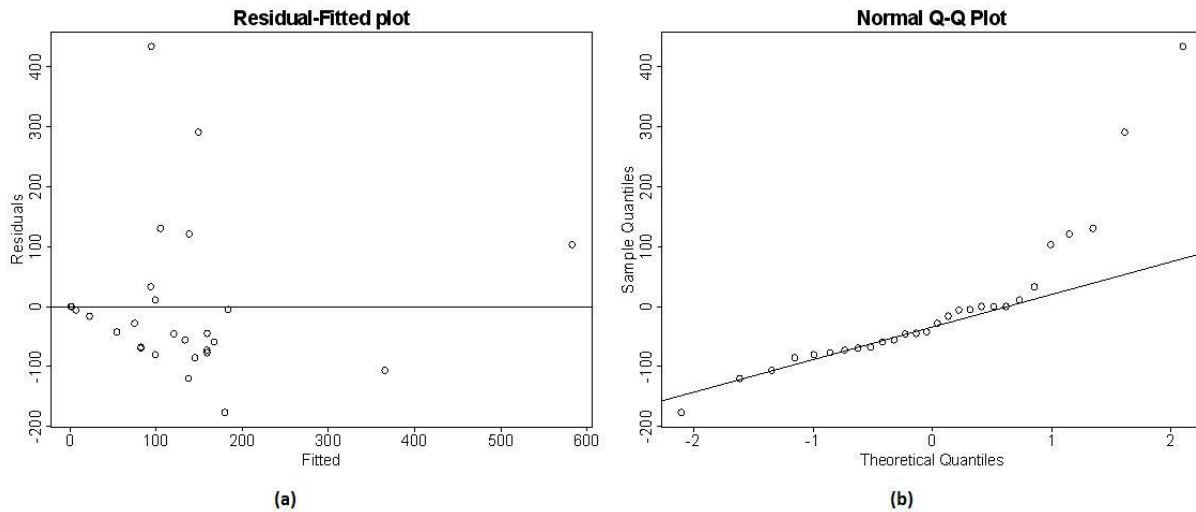
Sawmill size	Lumber production (m <sup>3</sup> /month)			Electricity (MJ/month)			MJ/m <sup>3</sup>
	Mean	Min	Max	Mean	Min	Max	Mean
SSM (n=10)	152.16	4.72	377.56	18943	1800	79200	124.5
MSM(n=16)	822.29	424.75	1415.84	318337	5796	1025640	387.1
LSM (n=5)	2624.03	2123.76	3539.61	584431	400000	1168358	222.7

Significant differences exist in carbon emission from electricity ( $p=0.0047$ ,  $F=6.6928$ ), in operating hours per week ( $p=0.004523$ ,  $F_0 = 6.2198$ ), and between lumber production levels per week ( $p=0.0001$ ,  $F=125.44$ ) for different sized sawmills. It was also found that significant differences exist in mean annual carbon emission between LSM and SSM but not with LSM and MSM, and SSM and MSM pairs. Likely, significant differences did not exist in mean operating hours per week between LSM and MSM but differences exist between other pairs (LSM-SSM and SSM –MSM). However, the significant differences exist mean weekly lumber production levels among different sawmills sizes.

Linear regression model was developed to predict the yearly C emission from sawmills (Eq. 3.7). The model was significant ( $P [F_0 \geq 16.42] = 4.184e-06$ ) and the coefficients of the predictors were also significant. The residual fitted plot (Figure 3.2a) suggests we can assume constant error of variance. The normal quantile-quantile (Q-Q) distribution plot (Figure 3.2b) suggests it is possible to assume normality of the errors though there appears to be a slight departure due to few outliers.

$$CE_{sm} = \beta_0 Lum_w + \beta_1 (Lum_w)^2 + exp \left\{ \beta_2 \left( \frac{1}{Opweek_{yr}} + Ohr_{wk} \right) \right\} \quad (3.7)$$

$$\beta_0 = 1.005e+00, \beta_1 = -1.402e-03, \beta_2 = 1.085e-19, \text{adjusted } R^2 = 0.623$$



**Figure 3. 2 Diagnostic plots of the predictors to estimate the yearly C emissions from sawmills.**

### 3.3.2 Carbon Emission and Energy Capture

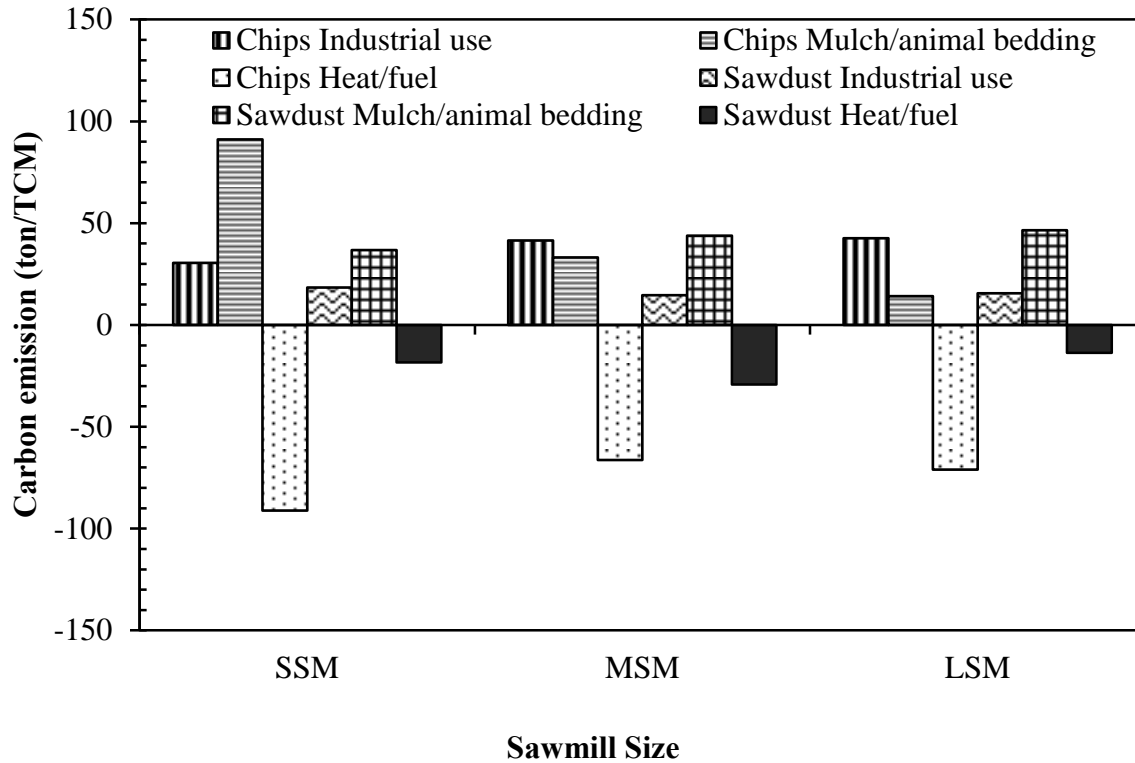
While producing 1,000 m<sup>3</sup> of lumber, a total of 2290 m<sup>3</sup> of green round wood is required and almost 64% of the volume is turned into wood residues (NREL, 2010, Bergman and Bowe, 2008). Approximately, 316.5 out of 680.13 metric tons of wood carbon are deposited as major mill/wood residues such as sawdust, chips and slabs. Carbon emissions from slabs were not considered in analysis because very few sawmills produced slabs in each sawmill size group. An average of 637.5, 422.50 and 383.22 green metric tons/TCM of chips and an average of 220.86, 262.50, and 232.71 green metric tons/TCM of sawdust were generated in SSM, MSM and LSM. Thus, an average of 286, 228.3, 205.3 tC/TCM of carbon were emitted with and without corresponding energy capture from SSM, MSM and LSM. It corresponds to an average of 212.5, 140.8, 127.7 tC/TCM from chips and 73.6, 87.6, 77.6 tC/TCM from sawdust in SSM, MSM and

LSM. The carbon emission amount from mill residue varied with the dimension of hardwood logs being processed. Typically, the smaller the diameter of log, the higher proportion of the mill residue. It also depends on shape such as green log taper.

Onsite carbon emission due to energy capture was greater from the combustion of chips than sawdust (Figure 3.3). Chips recaptured a greater amount of carbon when used for either heating or fuel purposes, i.e. 91.1 tC/TCM at SSM and 71 tC/TCM at LSM. Similarly, sawdust also recaptured a greater amount of carbon, i.e. 18.4 tC/TCM at SSM and 13.68 tC/TCM at LSM. This recaptured carbon from chips and sawdust as energy source, was released into the atmosphere at zero year of the lumber production. In the study area, timber product output data for 2001 and 2006 showed that an average 92% of carbon is emitted from using mill residue when used as energy source (USDA FS, 2010). However, such energy captures could account for 1.5% of the total energy consumption in U.S. (Perlack et al., 2005).

Industrial use of chips and sawdust was another source of carbon emission from the energy capture process. Carbon emission from industrial use of chips was greater in LSM and MSM while it was greater for sawdust in SSM and LSM. They were utilized either to generate heat or produce different short lived wood products, i.e. pulp and paper, pallets and barn that could lengthen carbon emission period. Similarly, carbon emission amount without energy captured from chips was significantly greater in SSM (91.1 tC/TCM) and it was greater in LSM (46.54 tC/TCM) from sawdust. Mill residue used for either mulching purpose on the farm or animal bedding lagged the carbon release time into the atmosphere than the residue used for heat or fuel purpose. This type of carbon emission, without energy capture, accounts for 8 % of the total carbon of mill residues (USDA FS, 2010). Therefore, mill residues used for either industrial

or farm purposes would be helpful to extend wood carbon life and increase carbon stock, as short lived wood product does.



**Figure 3. 3 Carbon emissions with and without energy capture processes from sawmill size.**

### 3.3.3 Energy Efficient Equipment and Avoided Carbon Emission

#### *(a) Energy efficient equipment*

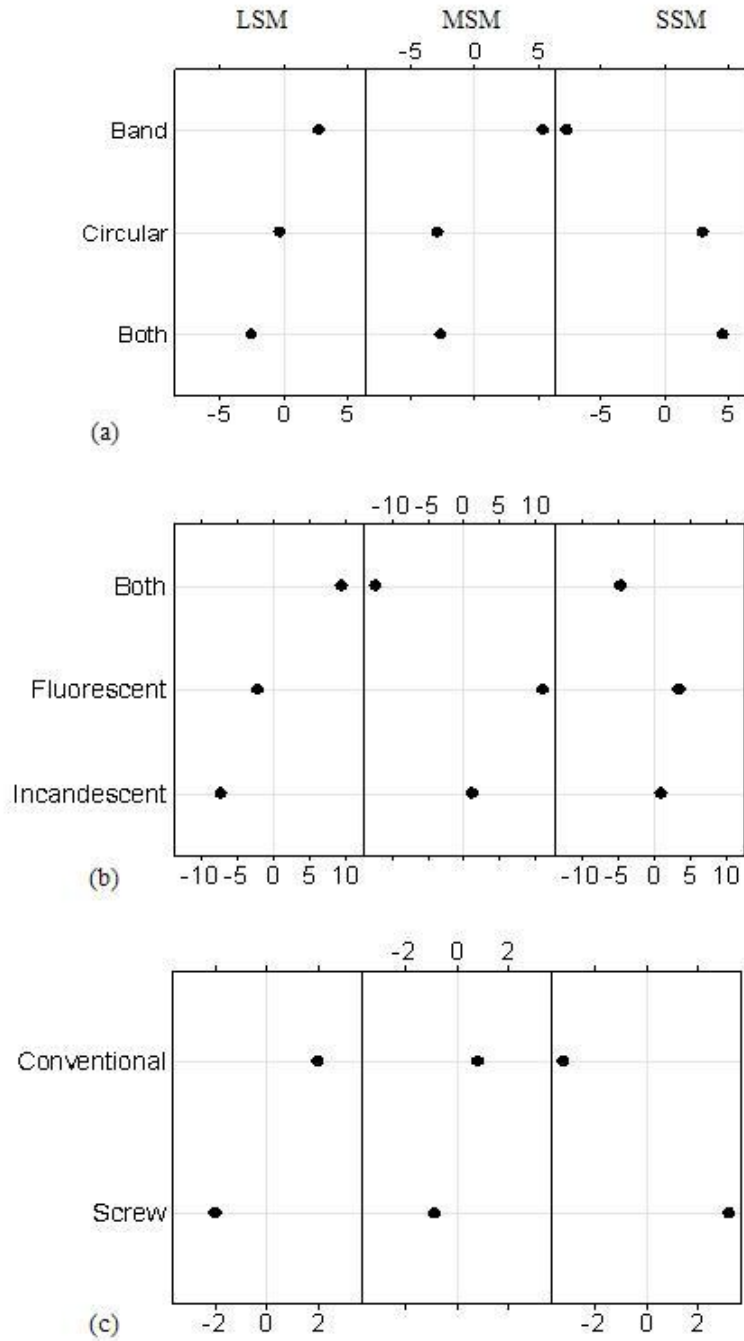
It was recently found that, MSM (13.9%) and LSM (8.3%) had upgraded efficient techniques to avoid carbon emissions, but SSM did not. However, every sawmill size had used efficient electric motor and had usually achieved at 80-90% efficiency level (Table 3.3). The efficiency level in energy consumption was coupled from the use of different efficient techniques such as head saws, light bulbs, and air compressors. Head saw used in sawmills were band (38.1%), circular saw (45.22%) and both types of head saws (16.7%). Lighting used in sawmills

varied from fluorescent bulbs (53.8%), incandescent bulbs (17.9%) and both (28.2%). Similarly, sawmills used conventional air compressor (45.7%) and/or highly efficient screw drive air compressors (45.7%) and both compressors (8.6%).

**Table 3. 3 Descriptive statistics of the efficient technique utilization in sawmill types.**

Efficient Techniques	SSM	MSM	LSM	Total
	( <i>n</i> =11)	( <i>n</i> =21)	( <i>n</i> =9)	
Upgraded for energy efficient	0.0%	13.9%	8.3%	22.2%
Efficient electric motor utilization	12.2%	36.6%	22.0%	70.80%
Efficiency level	( <i>n</i> =5)	( <i>n</i> =10)	( <i>n</i> =7)	
80-90%	13.6%	27.3%	9.1%	50.0%
91-94%	4.5%	13.6%	18.2%	36.4%
>94%	4.5%	4.5%	4.5%	13.6%

It was also found that the prediction intervals on the random effects (Fig 3.4) confirmed that the conditional distribution of the random effects of air compressor types by sawmill size has much less variability than the conditional distribution of the random effects from head saw types and light bulb types. Standard deviation on carbon emission (tC/TCM) in lumber processing from the random effect of head saw types was 2.51, 4.37, and 6.25 for the LSM, MSM, and SSM, respectively. From the random effect of light bulb types, the standard deviation was 6.87, 11.764 and 4.13 for the LSM, MSM, and SSM, respectively. Similarly, the standard deviation from air compressor type was 1.62, 0.68, and 2.62 for the LSM, MSM, and SSM, respectively. The greater variation in conditional distribution of random effect from efficient techniques might be the consequences of smaller sample size. However, the linear mixed effect model confirmed that the use of efficient techniques does affect carbon emission of sawmills.



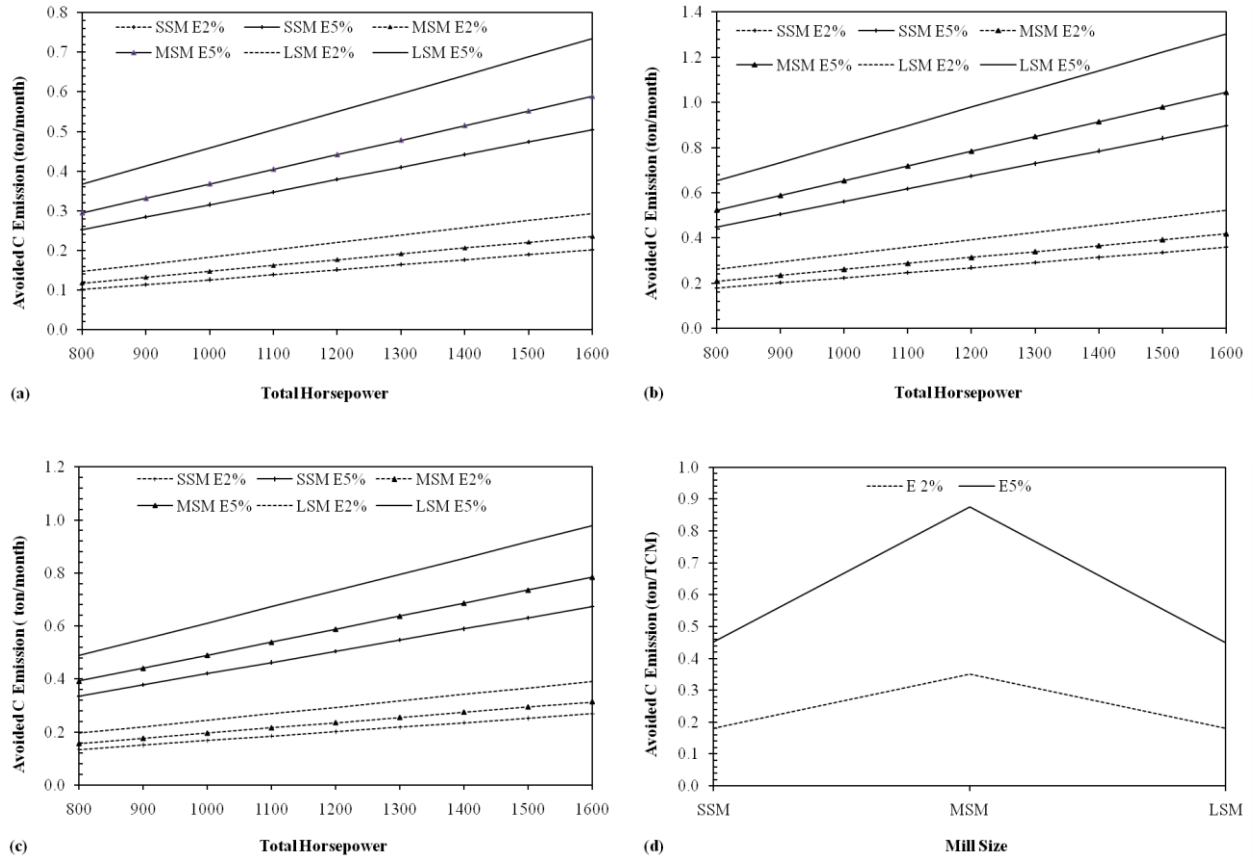
**Figure 3. 4 Diagnostic plot of variability of carbon emission (tC) per TCM of lumber processing by sawmill size at 95% prediction interval on the random effect of efficient techniques: (a) head saw types, (b) light bulb types, and (c) air compressor types.**



***(b) Avoided carbon emission***

An average carbon emission from electricity consumption in sawmills was 10.07 tC/month. Carbon emission could be reduced by 0.1 - 0.29 tC/month or 1-2.9%, when 2% electricity saving was achieved using both load and use factor of the machine at 0.6 in sawmills with a power range from 800 to 1600 hp (Figure 3.5a). Increased electricity saving level up to 5% of existing electricity consumption could increase avoided carbon from 0.25 to 0.73 tC/month or 2.5-7.2%. Greater amount of carbon emission could be avoided when both load and use factors were used at 0.8 (Figure 3.5b). In this case, avoided carbon emission amount could range from 0.18 to 0.52 tC/month (1.8 -5.2%) at a 2% electricity saving or from 0.45 to 1.3 tC/month (4.5 - 12.9 %) at 5% electricity saving. Likely, in the scenario of the combination of either load factor at 0.6 or use factor at 0.8 of machine in sawmills could achieve avoided carbon amount from 0.13 to 0.39 tC/month (1.3- 3.9%) and 0.34 to 0.98 tC/month (3.4 - 9.7%) at a 2% and 5% electricity saving level, respectively (Figure 3.5c).

In the base case, greater amount of avoided carbon emission could be achieved from electricity saving in MSM followed by LSM and SSM. This avoided carbon emission amount could range from 0.2 to 0.9 tC/TCM (2.13% at SSM -5.14% at MSM) from onsite and offsite electricity consumption, when 2% to 5% electricity saving was achieved during lumber production (Figure 3.5d). Though avoided carbon emission amount was less, it could play a significant role in mitigating greenhouse gaseous impact in Appalachian region in the long run, if it is accounted for the whole year production level and the total number of sawmills across the region. This avoided carbon could be instrumental in offsetting carbon emission burden from wood industries. For large sawmills size, increasing electricity saving could be beneficial in abating carbon emission as well as adopting carbon cap and trade policy.



**Figure 3.5** Avoided C emission using motor master in sawmills: (a) Total Hp at 0.6 load factor and use factor, (b) Total Hp at 0.8 load factor and use factor (c) Total Hp at 0.6, 0.8 load factor and use factor, and (d) at sawmill size category.

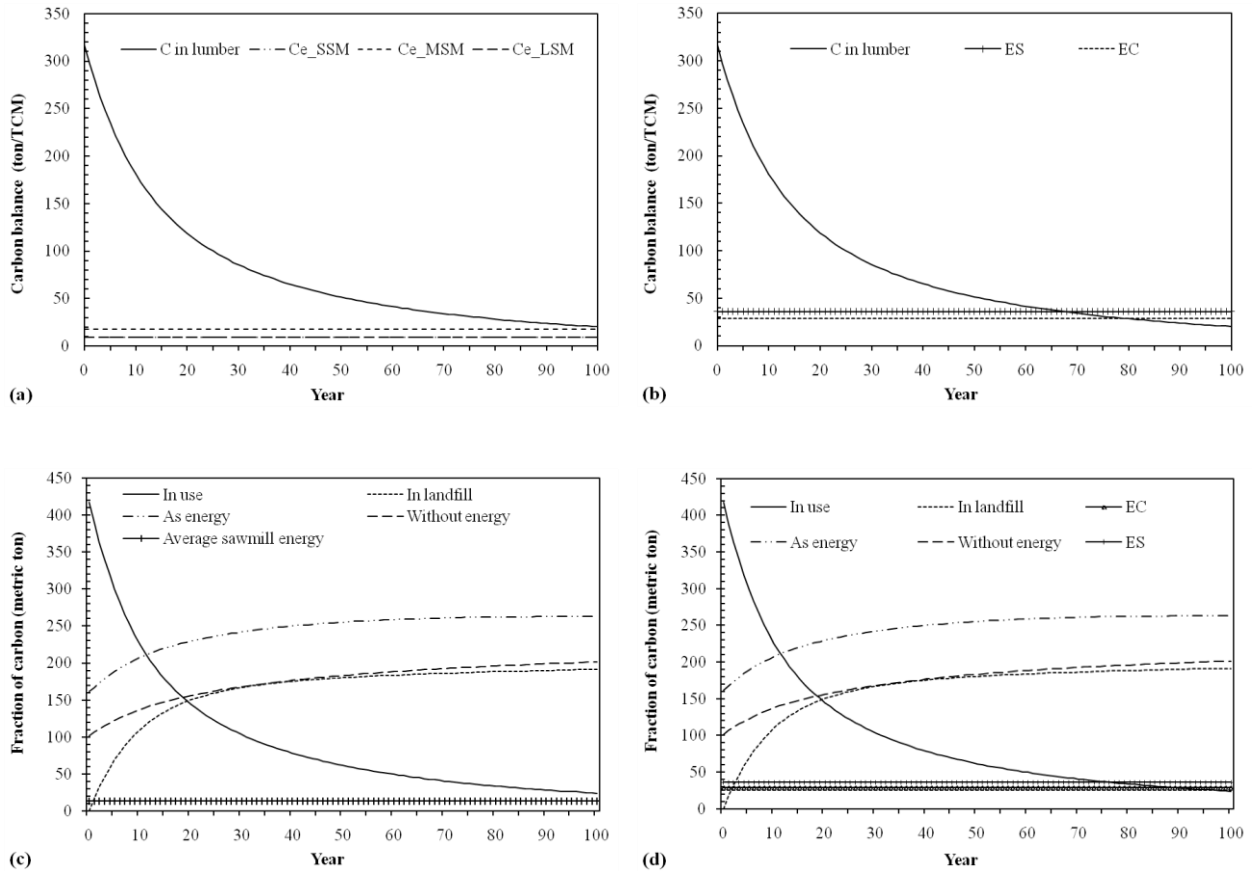
### 3.3.4 Carbon Balance in Lumber Production

The credit carbon balance accounts for 2.9, 5.5, and 2.8 % of the net debit carbon balance of lumber (316.5 tC/TCM) at the zero year of lumber production in the SSM, MSM and LSM, respectively. Effect of this credit carbon balance was not significant in the net debit carbon balance of lumber at first order of carbon decay up to 100 years (Figure 3.6a). However, it could affect after the useful life period of 100 years, i.e. beginning of the time period that lumber

would be discarded from their use purpose and disposed at landfills. The low credit carbon balance could be attributed to low electricity consumption by sawmills and it could be increased when other energy sources consumed were also considered. However, few sawmills reported consumption of other energy source used in lumber processing such as natural gas, and the total carbon emission amount from all energy sources involved in the lumber production averaged 13.1 ton/TCM.

Estimated total carbon emission amount from electricity consumption (*EC*) was 28.5 tC/TCM and it accounts for 9% of the carbon stored in the processed lumber. *EC* bisects carbon balance of lumber in 100 years of its useful life period at year 79, where the amount of carbon remained in lumber at first order of decay rate becomes equivalent to *EC* (Figure 3.6b). The payoff period (*PP*) begins after year 79 and reduced the carbon accountability period of lumber in its useful life by 21%. Similarly, 35.91 tC/TCM of credit carbon balance generated from all energy sources (*ES*) accounted for 11.35 % of the carbon balance in lumber. *ES* also bisects carbon balance of lumber at year 67 and shortens carbon accountable period of the lumber almost by 33 % (Figure 3.6b). Hence, carbon emitted from lumber after the bisected year would be equivalent to the amount of carbon debt created by credit carbon balance from lumber processing. The higher the debt carbon balance is, the early *PP* and consequently lower the carbon accountability in useful life period of the lumber would be. This *PP* of credit carbon would vary depending on the hardwood tree species used for lumber processing because the carbon content value among tree species differs. Debt carbon from lumber would attribute more if accounted cumulative carbon emission that occurred from harvesting of timber, transportation of lumber and energy consumed in lumber used for. Therefore, to neutralize such carbon debt,

reforestation of the harvested area should be conducted timely to pay off the credit carbon balance.



**Figure 3. 6 Effect of credit carbon balance in carbon balance of lumber and fraction of carbon disposition in sawlogs at 100 years period: (a) and (b) carbon balance by carbon emission level and energy consumption, (c) average sawmill energy consumption, and (d) electricity consumption (*EC*) all energy sources (*ES*).**

Lumber processing of  $1000 \text{ m}^3$  sawlogs contains an average of 680 metric tons of carbon. This carbon disposition pattern of sawlogs was significantly affected by the generated credit

carbon balance. An average credit carbon balance generated from all energy sources in lumber processing at sawmills only affected the carbon disposition pattern in landfills (Figure 3.6c). The generated carbon credit balance from only *EC* affected the period of carbon disposition pattern of sawlogs and the *PP* of credit carbon begins either for fraction of carbon in use at last 11 years of useful life or for fraction of carbon in landfills at first 3 years (Figure 3.6d). Likely, credit carbon balance from *ES* also affected the fraction of carbon in use and reduced carbon disposition period to 76 years (Figure 3.6d). It also affected fraction of carbon disposition period in landfills for first 3.5 years.

Accounting credit carbon balance against the carbon stored in wood product showed the similar pattern of shortening useful life period for both lumber at first order of decay (Figure 3.6a and 3.6b) and fraction of carbon disposition pattern in sawlogs (Figure 3.6c and 3.6d). Though credit carbon balance shortened useful life period of wood products, it tentatively estimated carbon accountability period of the lumber similar to the half life of solid wood products in single-family housing (75-80 years) (Skog and Nicholson, 1998; Skog, 2008; Lippke et al. 2010). When accounted credit carbon balance at year zero of lumber production, it just lowered the net carbon balance and showed the regular trends of carbon disposition as reported by Smith et al. (2006). However, deduction of carbon from lumber is not possible at its production year. Paying off of such generated credit carbon balance from re-growth or reforestation of the harvested area would not be possible in the same harvest year and concurrently it would be also augmented by the fuel consumption involved in the artificial regeneration process. A similar study addressed how to pay off such carbon debt in Massachusetts (MCCS, 2010), while producing of an equivalent amount of energy from woody biomass and fossil fuel burning. Almost 9 tons of carbon debt occurred from the utilization of

woody biomass energy. It could be recovered in 32 years by forest growth and after the benefit of burning woody biomass begins to accrue. Therefore, accounting the *PP* for carbon emission from wood product processing against the carbon stored in wood product in its useful life period would be reliable measures to compensate carbon emission amount from energy consumed in wood processing.

### **3.3.5 Carbon Flux from lumber processing**

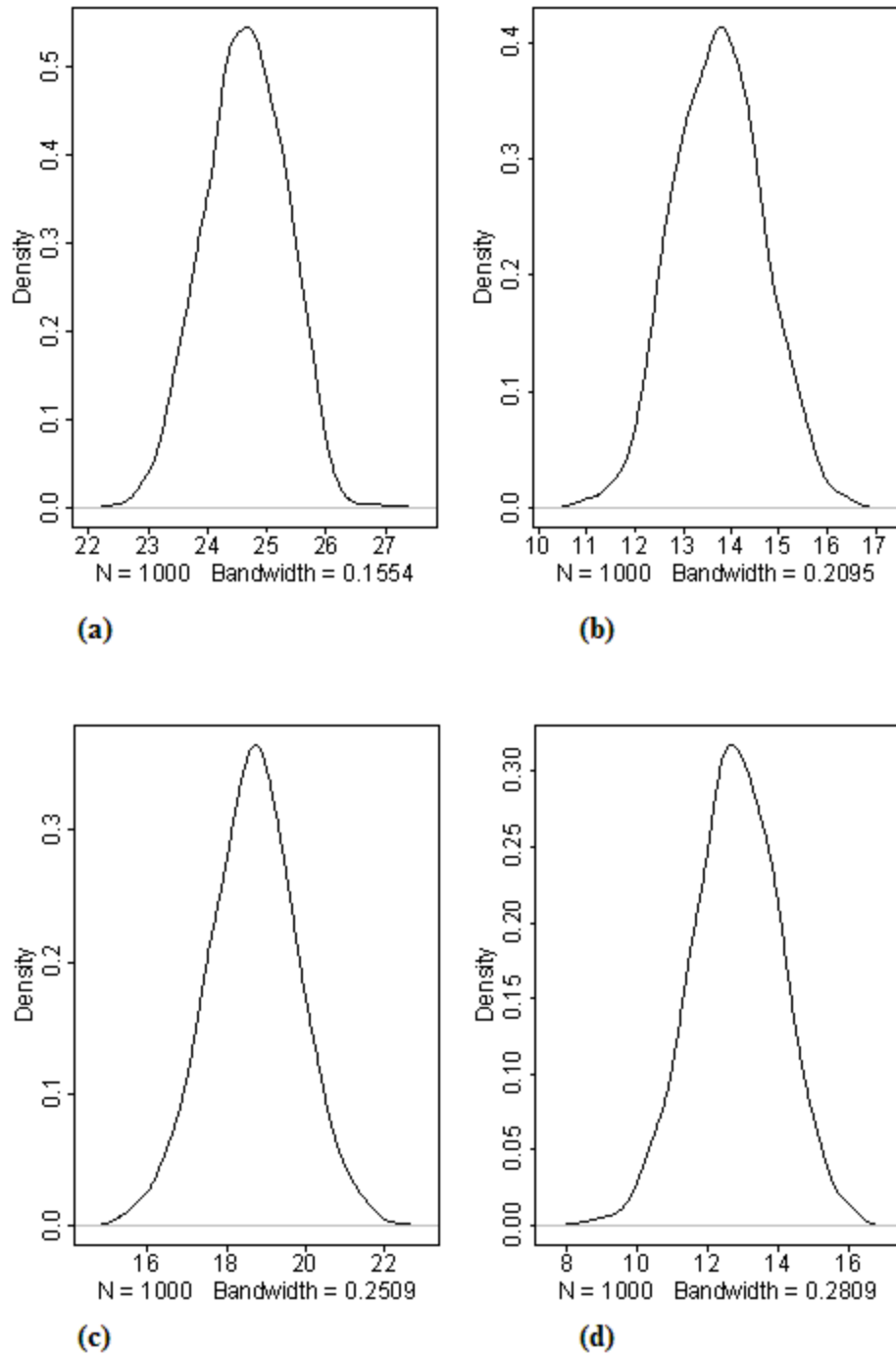
More carbon was emitted in the lumber processing mainly from the generated mill residues. Carbon flux from the use and no use of mill residues was 96.56 tC/TCM as energy capture, 55.3 tC/TCM as industrial use, 88.51 tC/TCM as farm manure, and 123.8 ton/TCM as others. The use and no use of mill residues increases the atmospheric carbon level from zero year of lumber production to 5 years depending on what purposes they are used for (Karjalainen et al., 2002; Skog, 2008; Zeng, 2008; Sharma, 2010). Carbon flux was also instigated by export of the lumber. An average of 6.7% of lumber produced was exported and it reduced carbon stock of lumber production place to 93.3%.

### **3.3.6 Sensitivity Analysis of Carbon Emission from Lumber Processing**

In the base case, the mean carbon emission from electricity consumption would be  $24.63 \pm 0.68$  tC/TCM during processing of hardwood lumber in sawmills in the Appalachian region. The carbon emission from electricity consumption would range from 23.28 to 25.88 tC/TCM (Figure 3.7a) at 2.5 % and 97.5% quantile distribution, respectively. In SSM, the mean carbon emission would be  $13.73 \pm 0.92$  tC/TCM ranging from 12.03 to 15.55 tC/TCM (Figure 3.7b) at 2.5% and 97.5% quantile distribution, respectively. For MSM, the mean carbon emission from

electricity consumption was  $18.68 \pm 1.12$  tC/TM and ranged from 16.41 to 20.94 tC/TCM (Figure 3.7c) at 2.5% and 97.5% quantile distribution. Similarly, in LSM, the mean carbon emission was  $12.79 \pm 1.24$  tC/TCM and varied from 10.36 to 15.20 tC/TCM (Figure 3.7d) at 2.5% and 97.5% quantile distribution.

The upper range of carbon emission predicted in the base case was closer to the carbon emission estimated from the electricity consumption by CORRIM (Bergman and Bowe, 2008) and it shortened the carbon accountability period of lumber in a similar manner. The simulated mean carbon emission amount was greater than the estimated average carbon emission in sawmills of different size. The observed difference between the simulated mean carbon emission and the estimated mean carbon emission was due to variability in data and associated uncertainty of electricity consumption rate at sawmills. The simulated mean carbon emission of each case lied at 50% quantile distribution whereas the estimated mean carbon emission lied at or below 2.5% quantile distribution. Since uncertainty always associates with the energy source for electricity generation and equipments used in sawmills, it would be better to use upper range of the simulated carbon emission (tC/TCM) for sawmill estimate.



**Figure 3. 7 Probability density plot of carbon emission (tC/TCM) from electricity consumption in lumber processing: (a) Overall average (b) SSM, (c) MSM, and (d) LSM.**



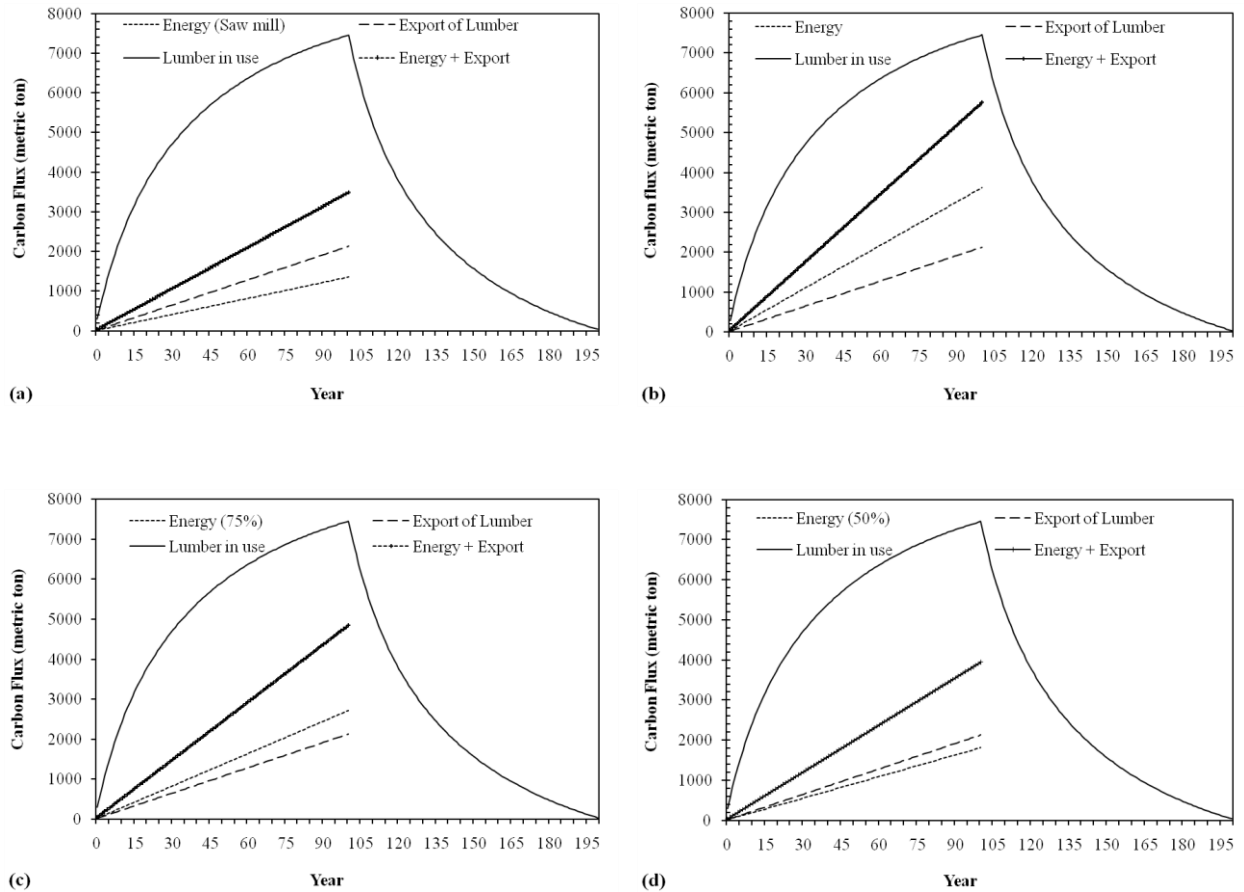
### 3.3.7 Scenario Analysis of Carbon Flux from Lumber Processing

The consequence of cumulative carbon emission from energy sources was observed in the cumulative carbon balance at the first order of carbon decay in the lumber production cycle of 100 years. In the base case, the  $CCF_{lumber}$  (21.1 tC/TCM) was 57.2 % higher than the cumulative carbon emission from electricity (13.1 ton/TCM) at sawmills for 100 years of lumber production (Figure 3.8a). However, the combined carbon flux from the electricity and export did not affect carbon stored in the produced lumber because the  $CCFR$  ranged from 0.12 to 0.42 from year zero to year 100.

The cumulative carbon emission from the total energy consumption and export of lumber could affect the cumulative carbon balance in lumber (Figure 3.8b). In this case, the  $CCFR$  from the all  $CCF_{energy\ source}$  consumption ( $ES$ ) (104.57 GJ/TCM) and  $CCF_{export}$  was 0.19 to 0.77 for the hardwood lumber production years of 0 -100. Thus, at the end of 100 years of production period, only 23% of the  $CCB_{lumber}$  would be available to account as the net debit carbon balance. Therefore, a great amount of carbon emission would affect the  $CCB_{lumber}$  production period and it would also discount such credit carbon balance at later years of the wood product life.

When 25% of the carbon emission from all energy source consumption was reduced, the  $CCFR$  would range from 0.16 at zero years to 0.65 at 100 years (Figure 3.8c). In this situation, 45% of the carbon in the lumber would be available to account as net  $CCB_{lumber}$  at 100 years. Similarly, if reducing 50% of carbon emission from all energy source consumption (Figure 3.8d), it could have the similar effect as carbon flux created from electricity and export by sawmills (Figure 3.8a). But the  $CCFR$  would range from 0.13 to 0.53. Thus, either reducing carbon emission/energy consumption rate or decreasing export of the lumber would help increase accountability of carbon balance in the lumber production for a long time period. Energy

consumption could be reduced by installing a waste oil burner for burning the waste oil to heat the plant and office areas. It saves the waste oil disposal cost and reduces the potential of a demining from spill and also less consumption of natural energy. But the waste oil installation factor depends on the quantity of waste oil generated by sawmill.



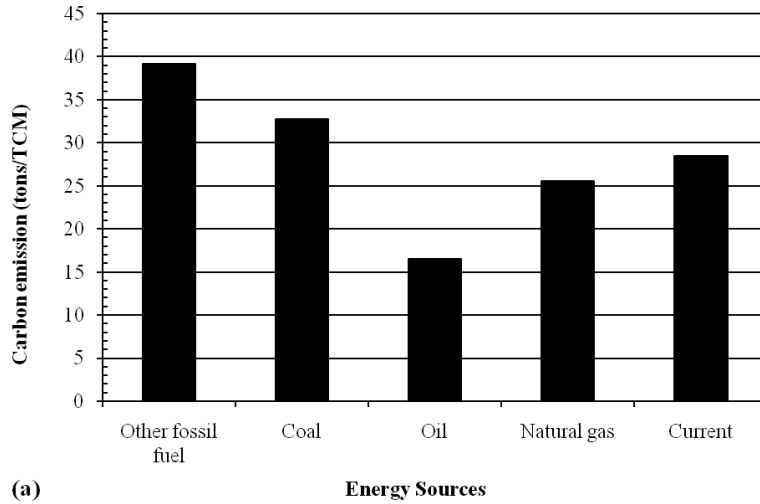
**Figure 3. 8 Atmospheric carbon fluxes from hardwood lumber processing in 100 years: (a) average electricity consumption at sawmills (b) all energy source consumption, (c) 25% reduction in all energy source consumption, and (d) 50% reduction in all energy source consumption.**

### 3.3.8 Carbon Emission under Different Energy Sources

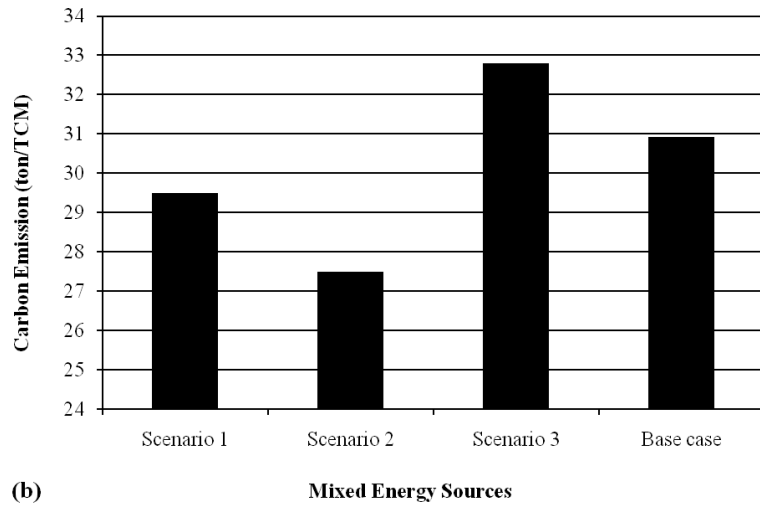
Since a great amount of electricity is required for lumber processing (607.2 GJ/TCM, Bergman and Bowe, 2008), it increases the atmospheric carbon level significantly. Generating such amount of electricity from natural gas would emit carbon equivalent to an average carbon emission level from the current electricity generation from the mixed sources in the Appalachian region (Figure 3.9a). Carbon emission from single source of electricity generation such as fossil fuel would be greater followed by coal. Therefore, the electricity generated from an appropriate mixture of energy sources could help avoid certain amount of credit carbon balance.

In figure (3.9b), the base case represents electricity generation from the mixed energy sources in central Appalachian region, scenario 1 represents RFC WEST, and scenario 2 represents RFC EAST, and scenario 3 NYUP. The credit carbon balance was 30.92 tC/TCM, 29.5 tC/TCM, 27.2 tC/TCM, and 32.8 tC/TCM for the base case, scenario 1, scenario 2 and scenario 3 respectively (Figure 3.9b). Scenario 2 would create less credit carbon balance than scenario 1 and scenario 3, and base case. Though in scenario 3, coal source shared less percentage of electricity than other scenarios, the higher carbon content value per unit of coal attribute to the greater amount of credit carbon balance in the represented region. It could be coupled from the variation in calorific value of coal and oil though these shared greater percentage of electricity generation than in other scenarios. Though coal shared higher percentage of electricity generation in the scenario 1 and 2, the lower value of average carbon content per unit of electricity generation in the represented regions created less credit carbon balance. Eventually, the credit carbon balance would have less affect on the carbon balance from lumber production. However, coal is the major source of electricity generation supplemented by gas and these energy sources usually have higher carbon coefficient value per unit of electricity.

Thus carbon credit per unit of lumber processing would vary depending on the electricity supply sources and their mixed ratio.



(a)



(b)

**Figure 3. 9 Carbon emissions from electricity generation during hardwood lumber processing using: (a) single energy sources and current average, and (b) mixed energy sources.**

*Note: Carbon emission from energy sources is calculated based at their higher heating values and the average carbon dioxide emission is based on eGrid (US EPA 2010b), CO<sub>2</sub>: Fossil fuel = 0.851 kg/kWh; Coal = 0.713 kg/kWh; Oil, 0.358 kg/kWh; Gas = 0.556 kg/kWh; and Current = 0.62 kg/kWh.*

### **3.4. Conclusions**

Carbon emission from electricity consumption while per unit of processed lumber vary depending on sawmill size. This variation would be coupled to electricity generation sources and available equipment at sawmills while per unit processed lumber. The random mixed effect of the available equipments such as head saws types, light bulb types and air compressors types also fluctuate the credit carbon balance of a sawmill. Such carbon emission could be avoided to some extent if energy efficient motors and equipment were used, which would be beneficial in abating carbon credit balance. Although carbon stored in produced lumber increases carbon stock of the wood carbon pool and magnifies humans' carbon mitigation efforts, carbon flux occurs due to significant wood loss during sawmill processing. Not all carbon loss from mill residues would be immediately recaptured as an energy source and released into the atmosphere. Mill residue used for either for industrial or mulching and farm bedding use would help to store significant amount wood carbon from being emitted for the time period as short lived wood product does.

Carbon balance in lumber would be affected by the credit carbon generated during its processing. It could also impair the carbon accountability period of lumber during its useful life. Carbon disposition pattern of sawlogs would also be greatly affected by this credit carbon balance. Carbon flux from the export of lumber also decreases the carbon accountability of the cumulative lumber production in years. The greater the carbon flux ratio from energy and export, the lower the carbon accountability of the produced lumber would be. Carbon emission from electricity consumption could be minimized by using energy sources that have a lower carbon coefficient. Thus, appropriate mixed energy sources in the region would be helpful to minimize carbon emission from electricity consumption at sawmills.

## References

- Apps, M. J., Kurz, W. A., Beukema, S. J. and Bhatti, J.S. 1999. Carbon budget of the Canadian forest product sector, *Env. Sci. Policy* **2**, 25–41.
- Bergman, R. D. and Bowe, S. C. 2008. Life-Cycle Inventory of Hardwood Lumber Manufacturing in the Northeast and North Central United States, CORRIM: Phase II Final Report Module C, p 1-48.
- Blasing, T. J., Broniak, C. T. and Marland, G. 2005., The annual cycle of fossil-fuel carbon dioxide emissions in the United States. *Tellus B*, **57**: 107–115
- Birdsey, R. A. 2006. Carbon accounting rules and guidelines for the United States Forest Sector. *J. Environ. Qual.*, Vol. 35, 2006, 1518-1524.
- Brown, S., Lim, B. and Schlamadinger, B. 1998. Evaluating approaches for estimating net emissions of carbon dioxide from forest harvesting and wood products. Meeting Report, IPCC/OECD/IEA Programme on National Greenhouse Gas Inventories, Dakar, Senegal, 5-7 May 1998. pp. 20.
- Dias, A. C., Louro, M., Arroja, L., and Capela I. 2005. The contribution of wood products to carbon sequestration in Portugal. 2005.- *Ann. For. Sci.* **62** (8) 903-909 .
- Gopalakrishnan, B., Winn, G., Chauhari, S., Bhadra, S., and Sundaramoorthy, S. K., 2008. Integrated assessment report focusing on IOF WV Priorities. Wood industry assistance program. Supported by West Virginia development office-Energy efficiency program.
- Gower, S. T. 2003. Patterns and mechanisms of the forest carbon cycle. *Ann. Rev. Environ. Resour.* **28**, 169–204.

- Harmon, M. E., Harmon, J. E., Ferrell, W. K., and Brooks, D. 1994. 'Modeling carbon stores in Oregon and Washington forest products: 1900–1992', *Climatic Change* **33**, 521–550
- Ingerson, A. 2009. Wood products and carbon storage: Can increased production help solve the climate crisis? Washington, D.C.: The Wilderness Society pg 6.
- IPCC,2003. Intergovernmental Panel on Climate Change Estimation, Reporting and accounting of harvested wood products – Technical Paper. UNFCCC paper. pp 44.
- Karjalainen, T., Pussinen, A., Liski, J., Nabuurs, G.J., Erhard, M., Eggers, T., Sonntag, M., Mohren, F. 2002. An approach towards an estimate of the impact of forest management and climate change on the European forest sector budget: Germany as a case study. *Forest Ecology and Management* 162:87-103
- Kurz, W. A., Apps, M. J., Webb, T. M. & McNamee, P. J. 1992. The carbon budget of the canadian forest sector: Phase I, Information Report NOR-X-326, Forestry Canada, Northwest Region, Forestry Centre, pp. 93
- Lippke, B., Wilson, J., Meil, J. and Taylor, A. 2010. Characterizing the importance of carbon stored in wood products. *CORRIM special Issue*, March 2010, V.42, 5-14
- MCCS [Manomet Center for Conservation Sciences]. 2010. Massachusetts biomass sustainability and carbon policy study: Report to the Commonwealth of Massachusetts Department of Energy Resources. Walker, T. (Ed.). Contributors: Cardellichio, P., Colnes, A., Gunn, J., Kittler, B., Perschel, R., Recchia, C., Saah, D., and Walker, T. Natural Capital Initiative Report NCI-2010-03. Brunswick, Maine. pp.182.
- Micales, J.A. and Skog, K.E. 1997. The decomposition of forest products in landfills. *Int. biodeterior. Biodegrad.* 39:145-158.

- NREL [National Renewable Energy Laboratory].2010. Life cycle inventory database, <http://www.nrel.gov/lci/database/>, accessed December 20, 2011.
- Perlack, R.D., Wright, L.L., Turhollow, A.F., Graham, R.L., Stokes, B.J., Erbach., D.C. 2005. Biomass as feedstock for a bioenergy and bioproducts industry: The technical feasibility of a billion-ton annual supply. DOE/USDA Tech. Rep. DOE/GO-102005–2135. USDOE, Office of Scientific & Technical Information, Oak Ridge, TN, p. 78.
- Pingoud, K., Savolainen, I., and Seppala ,H. 1996. Greenhouse impact of the Finnish forest sector including forest products and waste management, *Ambio* **25**(5), 318–326.
- Pingoud,K., Perälä, A. L., and Pussinen, A. 2001. Carbon dynamics in wood products. *Mitigation and Adaptation Strategies for Global Change* 2001, 6: 91–111.
- Puettmann, M. E., Bergman, R., Hubbard, S., Johnson, L., Lippke, B., Oneil, E. and Wagner, F. G. 2010. Cradle to gate life cycle inventory of us products production: CORRIM phase 1 and phase 2 products. *CORRIM special issue*, March 2010, V.42, 15-28.
- Row, C. and Phelps, R.B. 1996. Wood carbon flows and storage after timber harvest. *Forests and Global Change Vol. 2: Forest management opportunities for mitigating carbon emissions*, Sampson, R.N., Hair, D., eds. American Forests. Washington, D.C. 27-58.
- Saud, P. 2011. Analysis of forest carbon balance in central Appalachia region. Master Thesis (draft) submitting to Division of Forestry, West Virginia University.
- Schlamadinger, B. J., Spitzer, G., Kohlmaier, H. and Deke, M. L. 1995, Carbon balance of bioenergy from logging residues. *Biomass and Bioenergy* 8(4), 221-234 (1995).
- Sharma, B.D. 2010. Modeling of forest harvest scheduling and terrestrial carbon sequestration. Dissertation Submitted for the degree of Doctor of Philosophy in Forest Resource Science, West Virginia University, 2010, 1-159.



- Skog, K .E. and Nicholson,G .A. 1998. Carbon cycling through wood products: The role of wood and paper products in carbon sequestration. *Forest Products Journal* 48:75-83
- Skog, K .E., Pingoud, K., Smith, J. E. 2004. A method country can use to estimate changes in carbon stored in harvested wood products and the uncertainty of such estimates. *Environmental Management*. 33(Suppl. 1): S65-S73.
- Skog, K. E. 2008. Sequestration of carbon in harvested wood products for the United States. *Forest product journal*. Vol 58. No.6 (June 2008): pages 56-72.
- Siau, J. F. 1984. *Transport processes in wood*. Springer-Verlag, NewYork. 245p
- Smith, J. E., Heath ,L, S., Skog, K .E., Birdsey, R. A. 2006. Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.
- USDA FS. 2010. Timber Product Output (TPO) Reports November 04, 2010  
[http://srsfia2.fs.fed.us/php/tpo\\_2009/tpo\\_rpa\\_int2.php](http://srsfia2.fs.fed.us/php/tpo_2009/tpo_rpa_int2.php), accessed January 20, 2011
- USDOE [US Department of Energy]. 2010. Energy Efficiency and Renewable Energy, Industrial Technologies Program, Release Date: September 21, 2010,  
[http://www1.eere.energy.gov/industry/bestpractices/software\\_motormaster.html](http://www1.eere.energy.gov/industry/bestpractices/software_motormaster.html))  
accessed February 15, 2011.
- USEIA [US Energy Information Administration].2010. Average retail price of electricity to ultimate customers, Report Released: November 2010  
<http://www.eia.doe.gov/cneaf/electricity/esr/table5.html>. (Accessed Jan 25, 2011)

- US EIA 2011. US Energy Information, Independent Statistics and Analysis, Voluntary reporting of greenhouse gases program fuel emission coefficients  
<http://www.eia.doe.gov/oiaf/1605/coefficients.html>) accessed March 2, 2011
- USEPA [US Environmental Protection Agency]. 2005. Emission Fact, Office of Transportation and Air Quality, EPA420-F-05-001 February 2005. pp 2.
- USEPA [US Environmental Protection Agency]. 2010a. Inventory of U.S. Greenhouse Gas Emissions and Sink: 1990-2008. April 15, 2010 U.S. Environmental Protection Agency, Washington, DC, pg 1-407
- USEPA[US Environmental Protection Agency ]. 2010b. Environmental Protection Agency, Emissions & Generation Resource Integrated Database (eGRID)  
<http://cfpub.epa.gov/egridweb/view.cfm>, accessed December 28, 2010.
- Werner, F., Taverna, R., Hofer, P., Richter, K. 2005. Carbon pools and substitution effects of an increased use of wood in buildings in Switzerland: first estimates. *Annals of For. Sci.* 62, 889-902.
- White, M. K., Gower, S. T., and Ahl, D. E. 2005. Life cycle inventories of roundwood production in northern Wisconsin: Inputs into an industrial forest carbon budget *Forest Ecology and Management* 219 (2005) 13–28
- Wilson, J.B. and Dancer, E. R. 2005. Gate to gate life cycle inventory of laminated veneer lumber production. *Wood and Fiber Science*, 37 CORRIM Special Issue, 2005, pp 114-127.
- Winjum, J. K., Brown, S. and Schlamadinger, B. 1998. Forest harvests and wood products: sources and sinks of atmospheric carbon dioxide. *Forest Science* 44:272-284.
- Zeng, N. 2008. Carbon sequestration via wood burial. *Carbon Balance and Management* 3:1-12

#### **4. SUMMARY**

Inclusion of parameters such as carbon loss from dead trees, forest fire along with timber removal and forest growth rate is essential to estimate future carbon balance of the timberland. The lower harvesting intensity of the existing timber stock volume, small amount of carbon removal from small fire and limited dead trees do not significantly affect the future forest carbon stock per hectare. However, the observed high mortality rate of trees could be a major factor to limit the sustainable increase of forest carbon stock in West Virginia. Increasing timber demand could be met with slight increases in existing harvesting intensity and making constant harvesting intensity for certain consecutive years. This would help to lengthen the rotation age of natural mixed hardwood forest and also increase forest carbon stock. Eventually, this strategy would employ the sustainable forest management practice and also undermine the effect of carbon emissions from fossil fuel consumption due to timber harvesting and processing.

Natural regeneration in forests, as applicable in the Appalachian region, entails no fossil fuel consumption in seedling production and plantation and thus results in zero carbon emission from regeneration process. Carbon emission from mechanized harvesting system and manual harvesting system did not differ significantly. The variations associated with the machine productivity and the tree size would influence the carbon emission level from harvesting systems to some extent. However, these variations would be significant when considering topographic factors attributed to the harvested area. In harvesting and residue extraction, the hauling process has a greater effect on carbon emission than other operational procedures. Though carbon emissions from fossil fuel consumption from harvesting systems are considerably lower than the carbon stored in harvested timber and logging residue, the forest carbon displacement rate would vary with forest group types, road types, hauling truck types, and payload sizes. Forest type

having lower carbon content per unit of harvested volume and hauling smaller payload would increase forest carbon displacement rate. In hauling, the distance travelled on gravel road and paved road, and payload variation of harvested timber dimensions would determine the magnitude of carbon emission. Therefore, hauling distance and truck payload size indicate a greater uncertainty of carbon emissions level, which increases the forest carbon displacement rate and reduce the accountability of carbon balance in harvested timber.

Different levels of credit carbon balance are generated from carbon emitted from electricity consumption depending on operation hours and lumber processing quantity of different sawmills sizes. This variation is attributed to electricity generated from different energy sources. Similarly it is also attributed to the available equipment and its energy efficiency level at sawmills while processing per unit of lumber. For example, different head saws, light bulbs and air compressors used in sawmills fluctuated the degree of credit carbon balance. Such generated credit carbon balance could be lowered to some extent if using energy efficient motors and equipment. During lumber processing, a substantial amount of carbon emission occurs due to wood loss as mill residue other than carbon stored in the processed lumber products. Not all carbon loss from mill residues, such as chips and sawdust, would be immediately recaptured as an energy source (e.g. heat/fuel source) in sawmills. The amount of mill residue that used for mulching and farm bedding would be significant to lengthen carbon release time period.

The generated credit carbon balance during lumber processing could impair the carbon accountability period of lumber during its useful life period. Carbon disposition pattern of sawlogs would also be greatly affected by this credit carbon balance. The greater the credit carbon balance, the shorter the debt payoff period would be, and the shorter the carbon accountability period of wood product in its useful life period. This payoff period could vary

depending on hardwood tree species. Carbon emission from energy consumption and carbon loss from export of hardwood lumber create carbon flux in the wood carbon stock. Such cumulative carbon flux from energy consumption and lumber export would reduce the accountability of carbon balance during lumber production in years. The greater the cumulative carbon flux ratio, the lower the carbon balance accounted from the lumber production. Such carbon flux ratio could be minimized by reducing energy consumption rate in lumber processing. One of the feasible options to reduce energy consumption is to install a waste oil burner to heat the plant and office areas and it also saves waste oil disposal cost depending on the quantity of waste oil generated in sawmill. Additionally, the use of different energy sources that has lower carbon coefficient value would be advantageous to supply the required amount of electricity to process per unit of lumber. An appropriate mixed energy source in the region would be helpful to minimize credit carbon balance from electricity consumption at sawmills.